US009483588B2

(12) **United States Patent**
Nehme et al.

(10) **Patent No.: US 9,483,588 B2**
(45) **Date of Patent: *Nov. 1, 2016**

(54) **SOLID IDENTIFICATION GRID ENGINE FOR CALCULATING SUPPORT MATERIAL VOLUMES, AND METHODS OF USE**

(71) Applicant: **Stratasys, Inc.**, Eden Prairie, MN (US)

(72) Inventors: **Ziad A. Nehme**, Richmond, TX (US); **Amer E. Mouawad**, Knoxville, TN (US)

(73) Assignee: **Stratasys, Inc.**, Eden Prairie, MN (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **14/335,028**

(22) Filed: **Jul. 18, 2014**

(65) **Prior Publication Data**

US 2014/0330419 A1 Nov. 6, 2014

Related U.S. Application Data

(63) Continuation of application No. 13/231,533, filed on Sep. 13, 2011, now Pat. No. 8,818,544.

(51) **Int. Cl.**

G06F 17/50	(2006.01)
B29C 67/00	(2006.01)
G06T 17/00	(2006.01)
G06T 17/10	(2006.01)

(52) **U.S. Cl.**

CPC ***G06F 17/50*** (2013.01); ***B29C 67/0088*** (2013.01); ***B29C 67/0092*** (2013.01); ***G06T 17/005*** (2013.01); ***G06T 17/10*** (2013.01)

(58) **Field of Classification Search**

CPC G06F 17/50; B29C 67/0092; B29C 67/0088; G06T 17/10; G06T 17/005

USPC 700/98, 106, 117, 118, 119, 120, 182; 703/1, 6; 705/400

See application file for complete search history.

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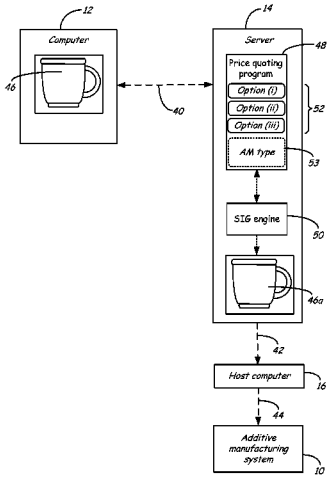
Primary Examiner — Charles Kasenge

(74) *Attorney, Agent, or Firm* — Westman, Champlin & Koehler, P.A.

(57) **ABSTRACT**

A method for calculating a support material volume, the method comprising generating a grid of cells for a tree data structure of a digital part, where the cells define a plurality of cell arrays, and pinging the cells of one of the cell arrays until a cell containing a subset of the tree data structure is reached or until each cell in the cell array is pinged, where if a cell containing the subset of the tree data structure is reached, then designating the reached cell and all remaining unpinged cells in the cell array as filled. The method also includes repeating the pinging step for each remaining cell array to determine a total filled volume, and subtracting a volume of the digital part from the total filled volume to determine a support material volume.

20 Claims, 22 Drawing Sheets



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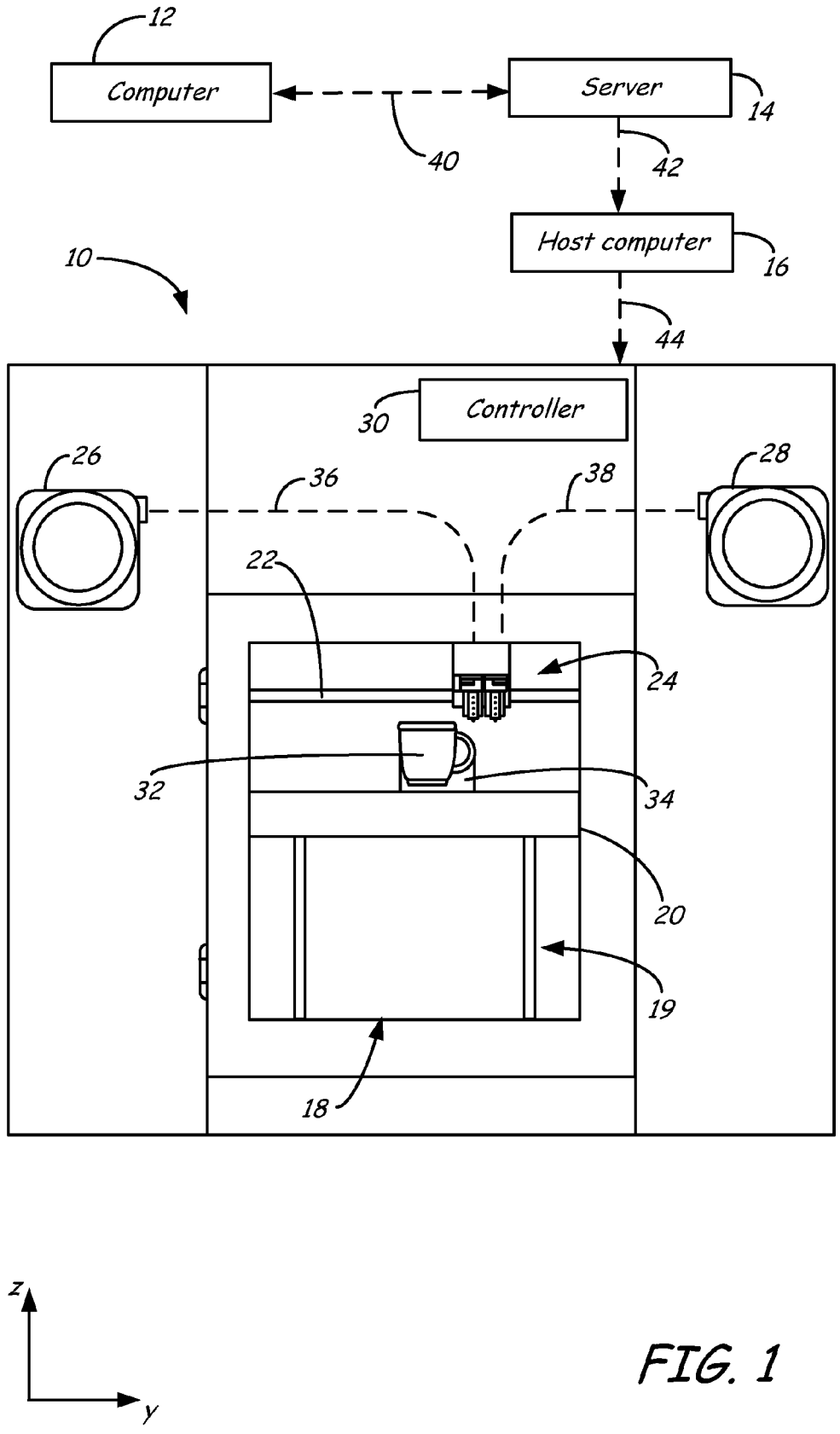
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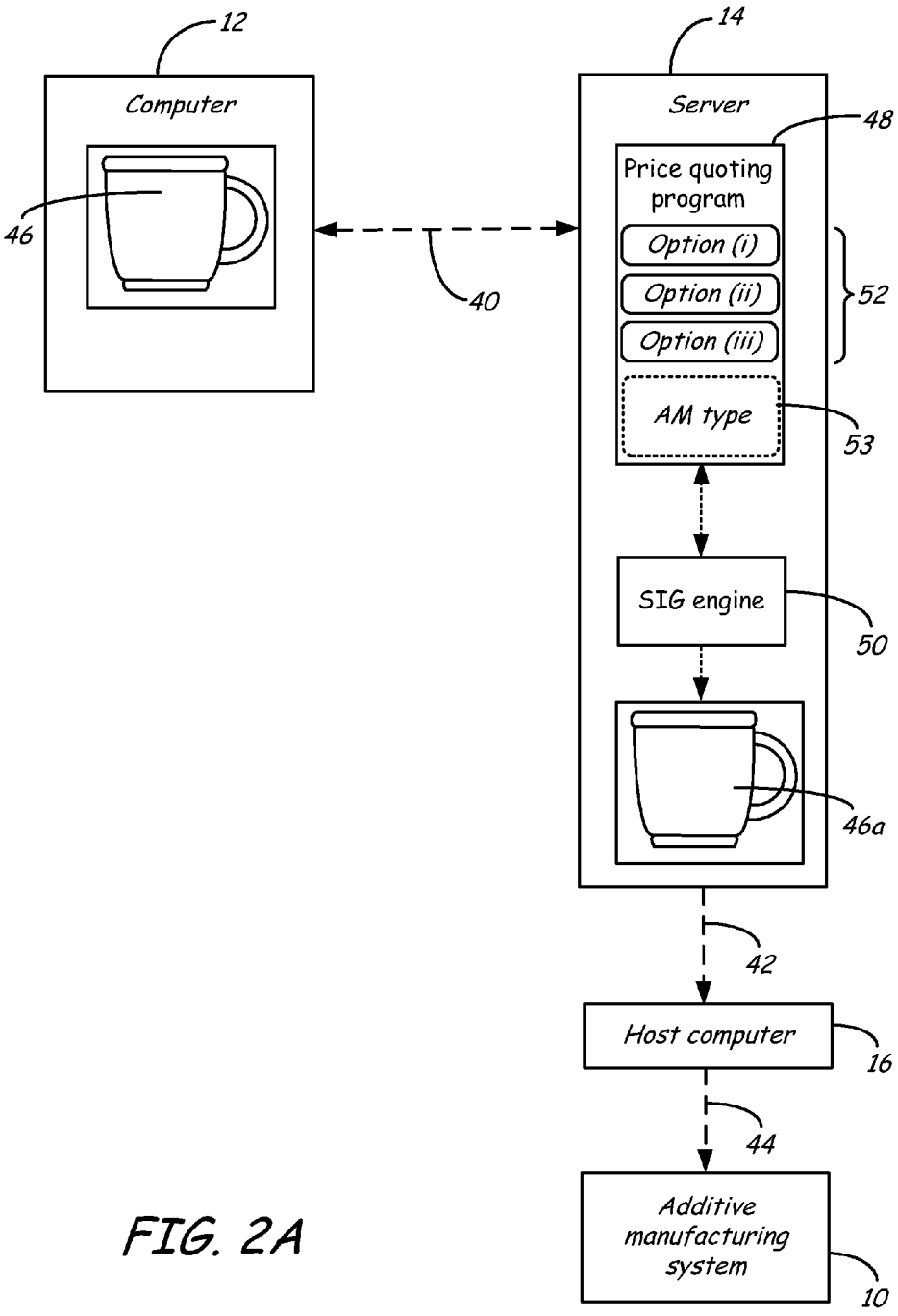
Server
14
40
42
Host computer
16
10
44
Controller
30
26
28
36
38
22
24
32
34
20
19
18
z
y

FIG. 1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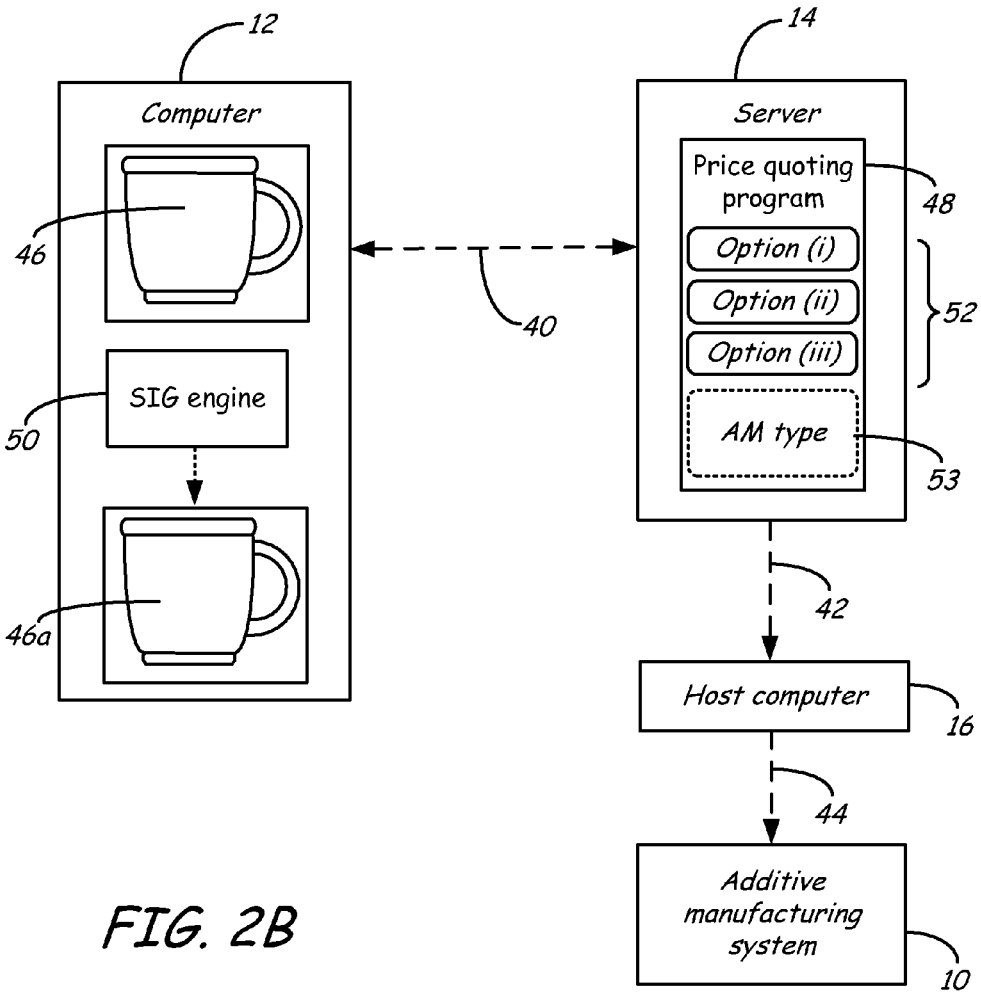
14
Server
48
Price quoting program
Option (i)
Option (ii)
Option (iii)
52
AM type
53
SIG engine
50
46a
42
Host computer
16
44
Additive manufacturing system
10

FIG. 2A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SIG engine
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46a
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14
Server
Price quoting program
48
Option (i)
Option (ii)
Option (iii)
52
AM type
53
42
Host computer
16
44
Additive manufacturing system
10

FIG. 2B

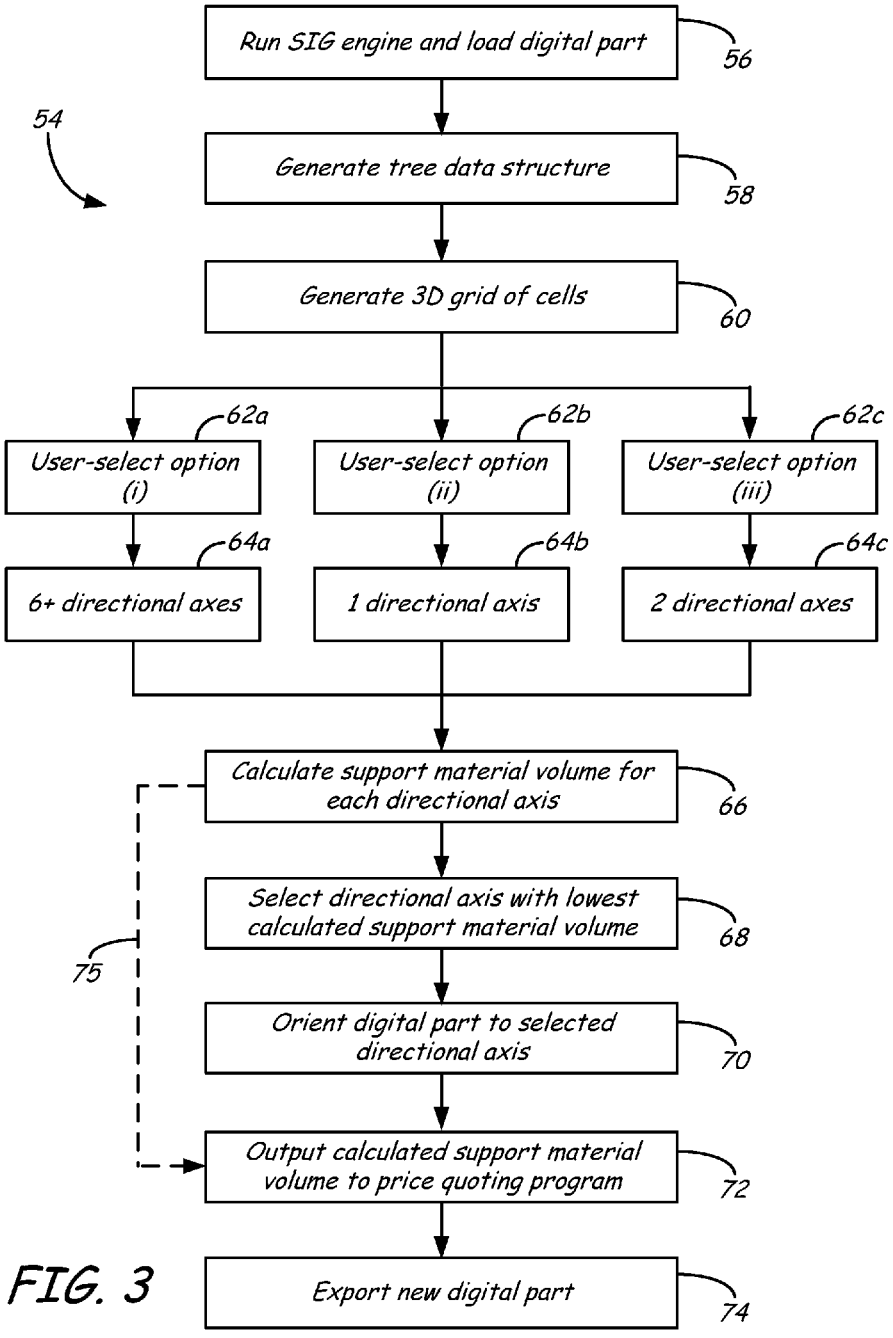

Run SIG engine and load digital part
56
54
Generate tree data structure
58
Generate 3D grid of cells
60
62a
62b
62c
User-select option (i)
User-select option (ii)
User-select option (iii)
64a
64b
64c
6+ directional axes
1 directional axis
2 directional axes
Calculate support material volume for each directional axis
66
Select directional axis with lowest calculated support material volume
68
75
Orient digital part to selected directional axis
70
Output calculated support material volume to price quoting program
72
Export new digital part
74

FIG. 3

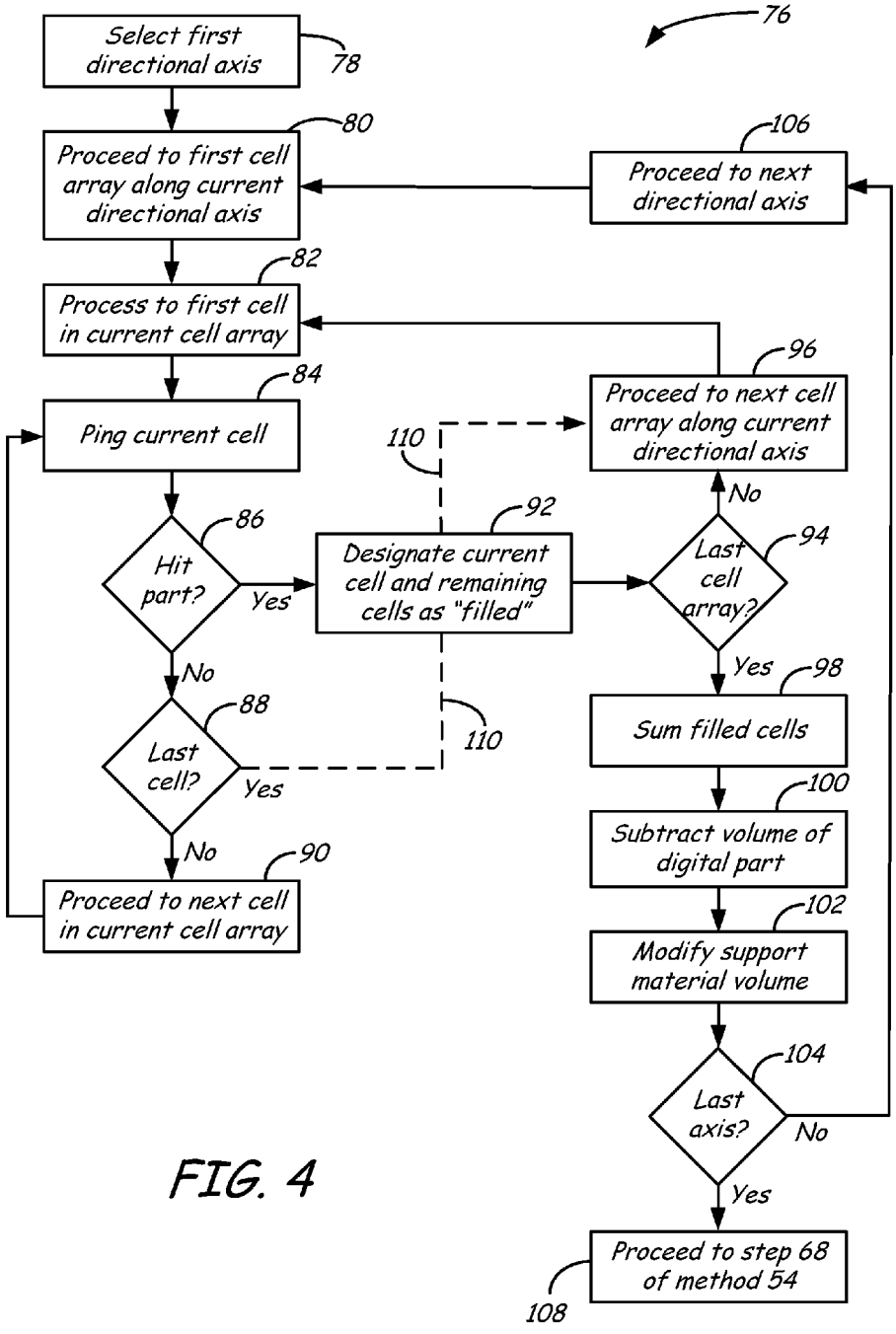

76
Select first directional axis
78
80
Proceed to first cell array along current directional axis
82
Process to first cell in current cell array
84
Ping current cell
86
Hit part?
Yes
No
88
Last cell?
Yes
No
90
Proceed to next cell in current cell array
92
Designate current cell and remaining cells as "filled"
110
110
94
Last cell array?
No
Yes
96
Proceed to next cell array along current directional axis
98
Sum filled cells
100
Subtract volume of digital part
102
Modify support material volume
104
Last axis?
No
Yes
106
Proceed to next directional axis
108
Proceed to step 68 of method 54

FIG. 4

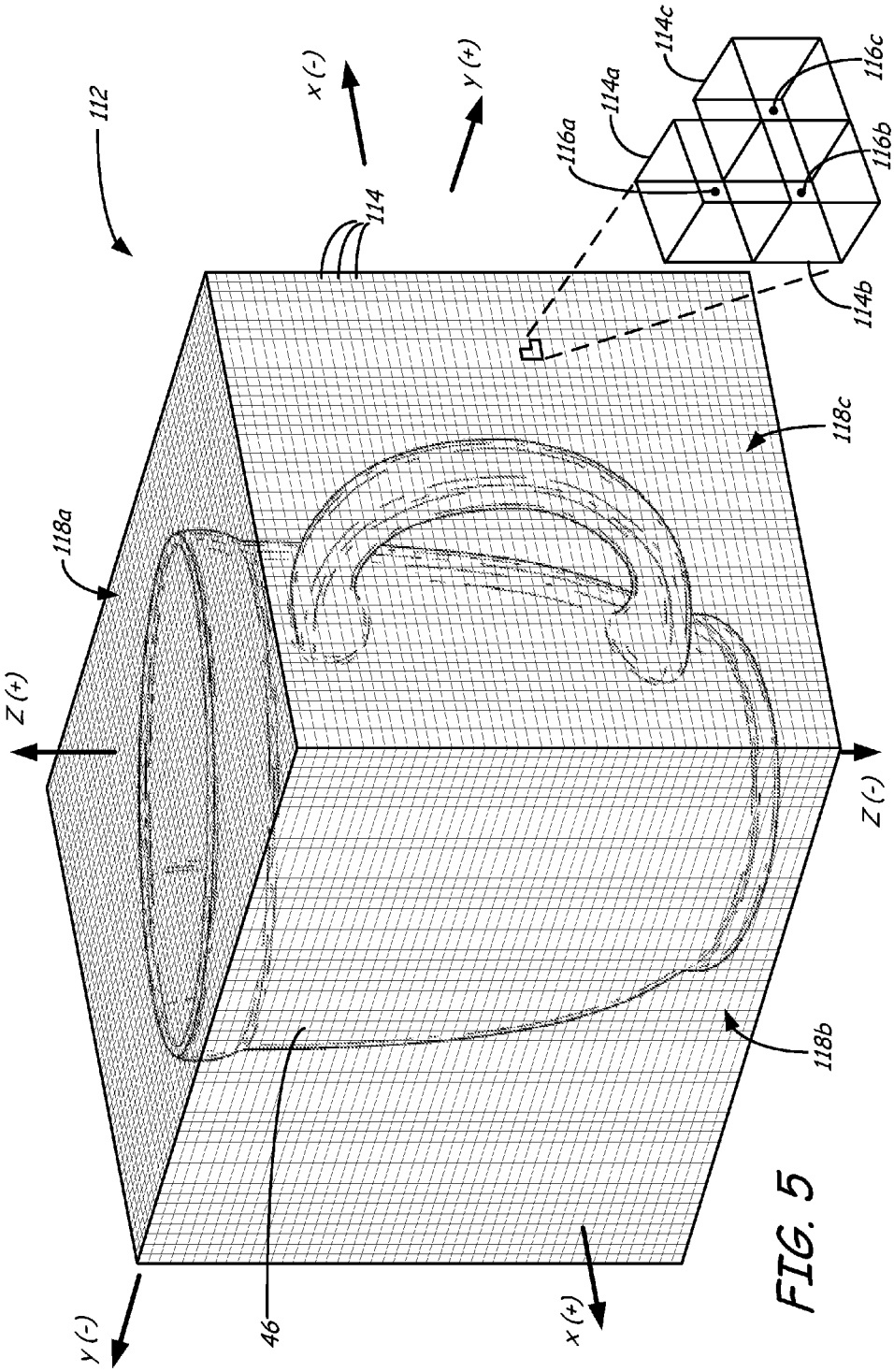

112
x (-)
y (+)
114
114c
114a
116c
116a
116b
114b
118c
118a
Z (+)
Z (-)
118b
46
y (-)
x (+)

FIG. 5

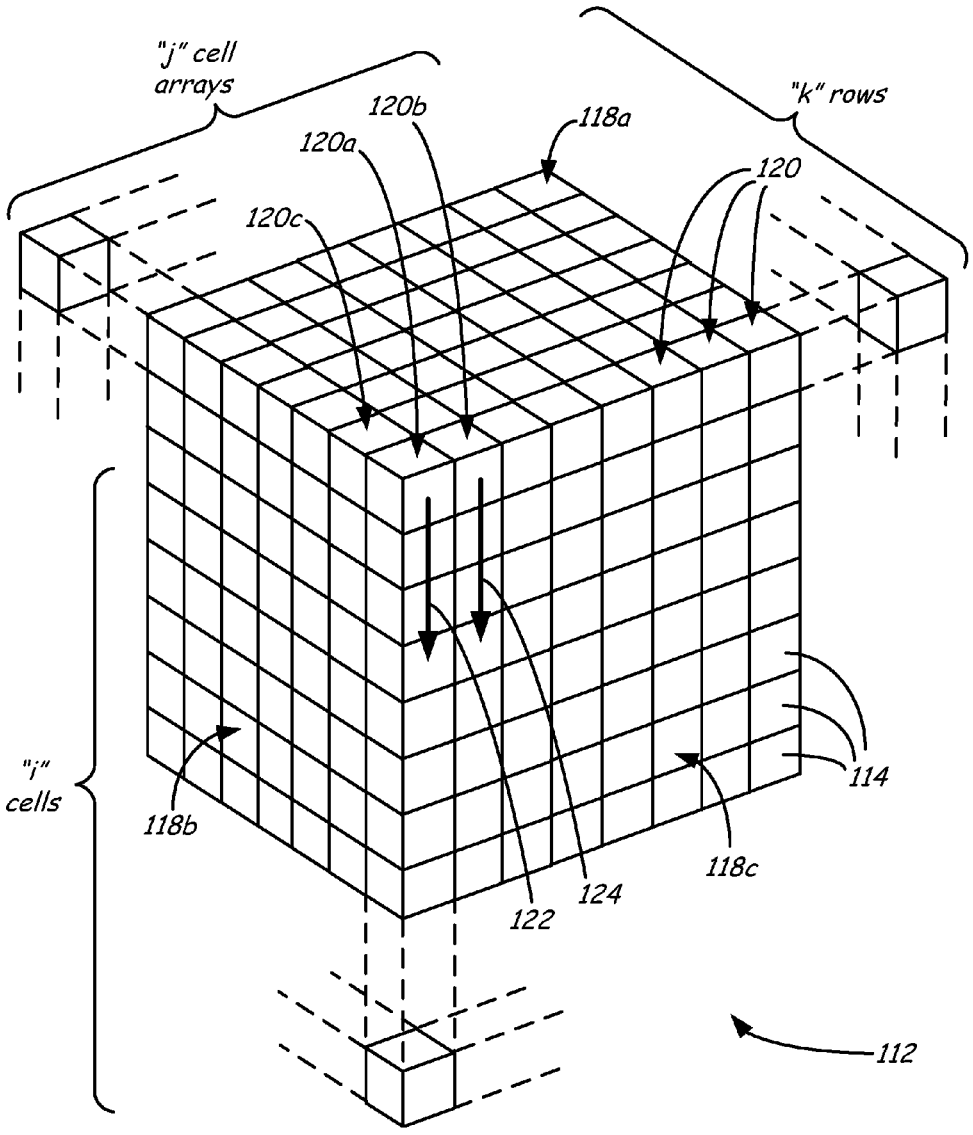

"j" cell arrays
"k" rows
120b
118a
120a
120
120c
"i" cells
118b
114
118c
124
122
112
z
x
y

FIG. 6

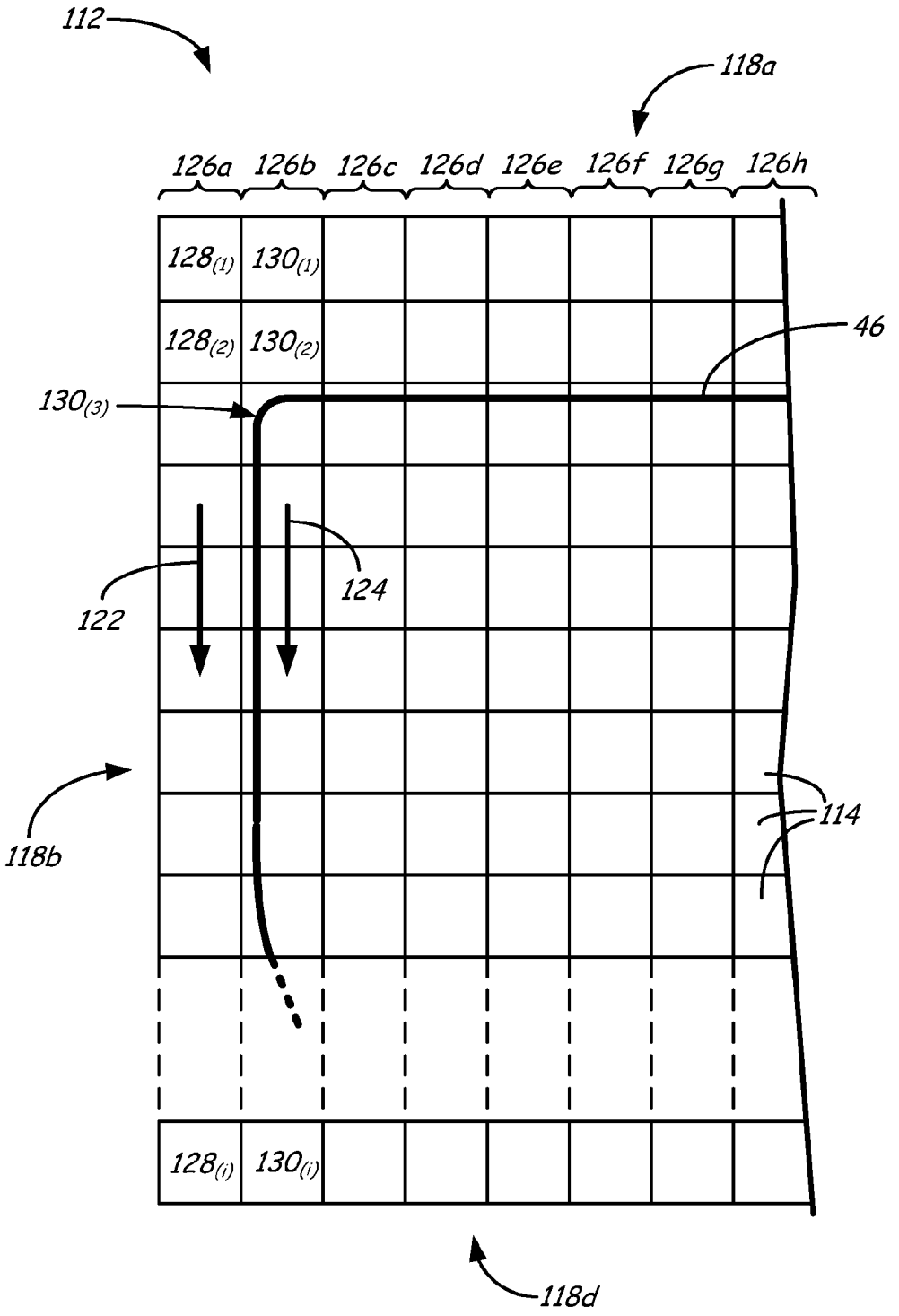

112
118a
126a
126b
126c
126d
126e
126f
126g
126h
128(1)
130(1)
128(2)
130(2)
46
130(3)
124
122
118b
114
128(i)
130(i)
118d
z
x

FIG. 7A

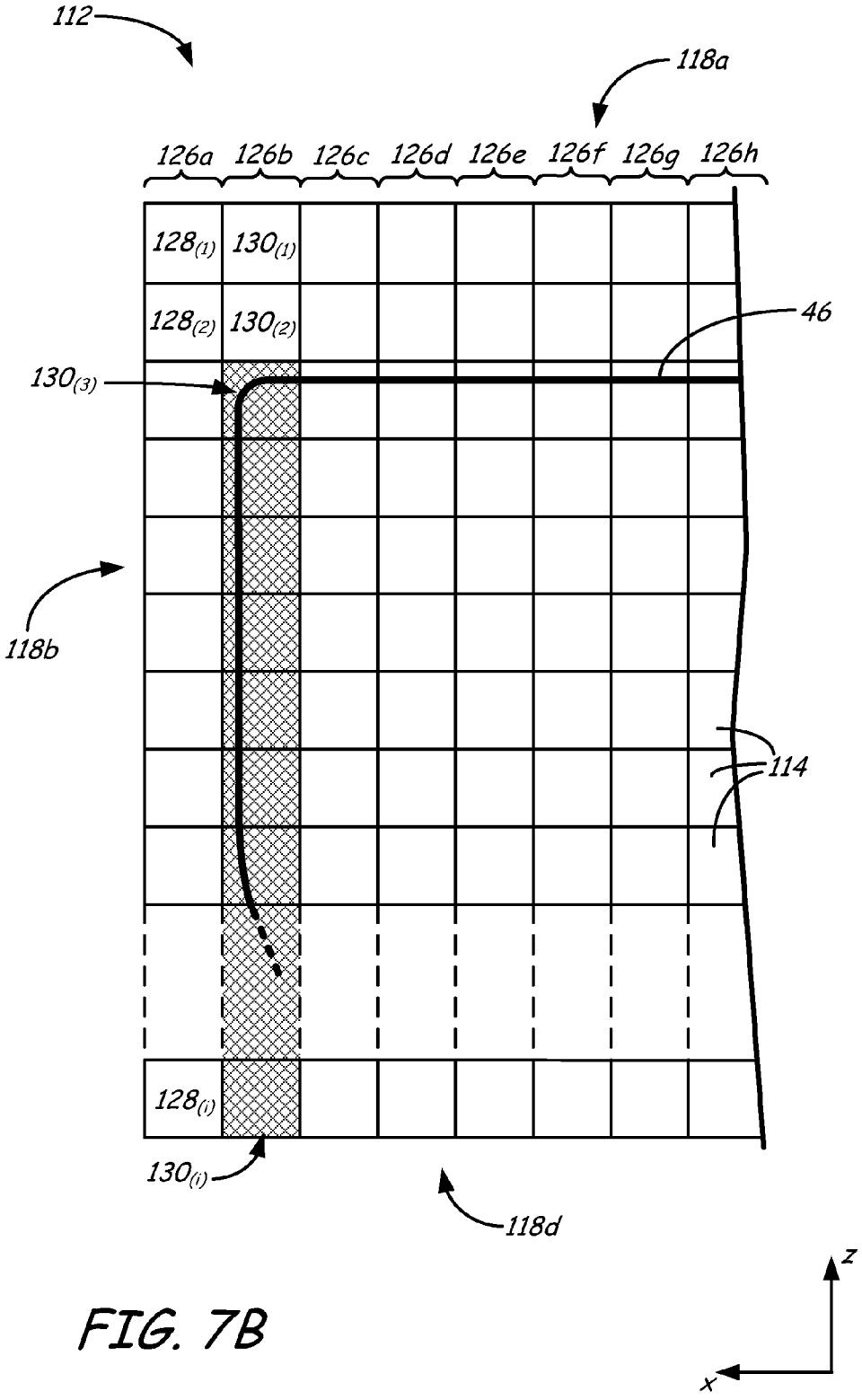

112
118a
126a
126b
126c
126d
126e
126f
126g
126h
128(1)
130(1)
128(2)
130(2)
46
130(3)
118b
114
128(i)
130(i)
118d
z
x

FIG. 7B

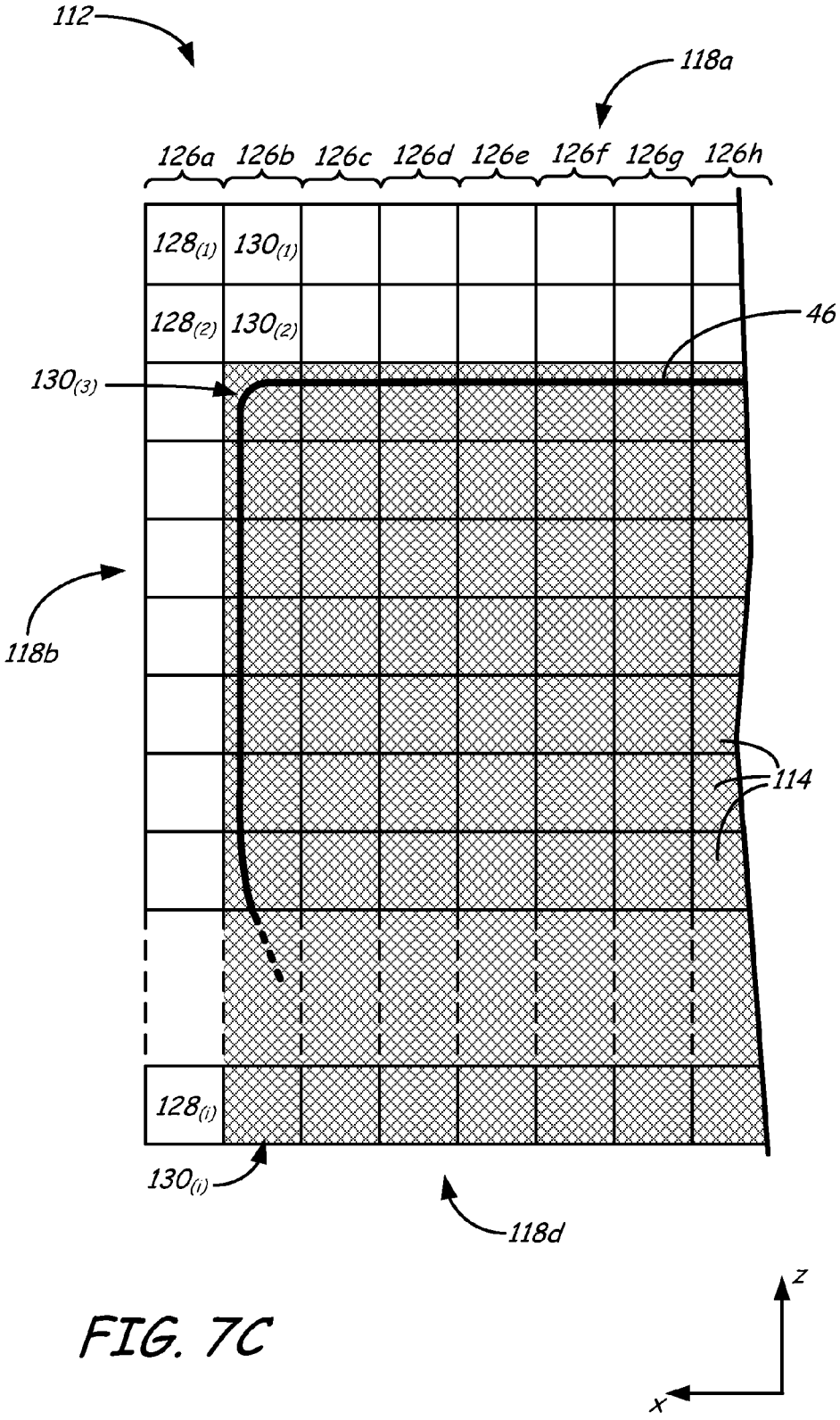

112
118a
126a
126b
126c
126d
126e
126f
126g
126h
128(1)
130(1)
128(2)
130(2)
46
130(3)
118b
114
128(i)
130(i)
118d
z
x

FIG. 7C

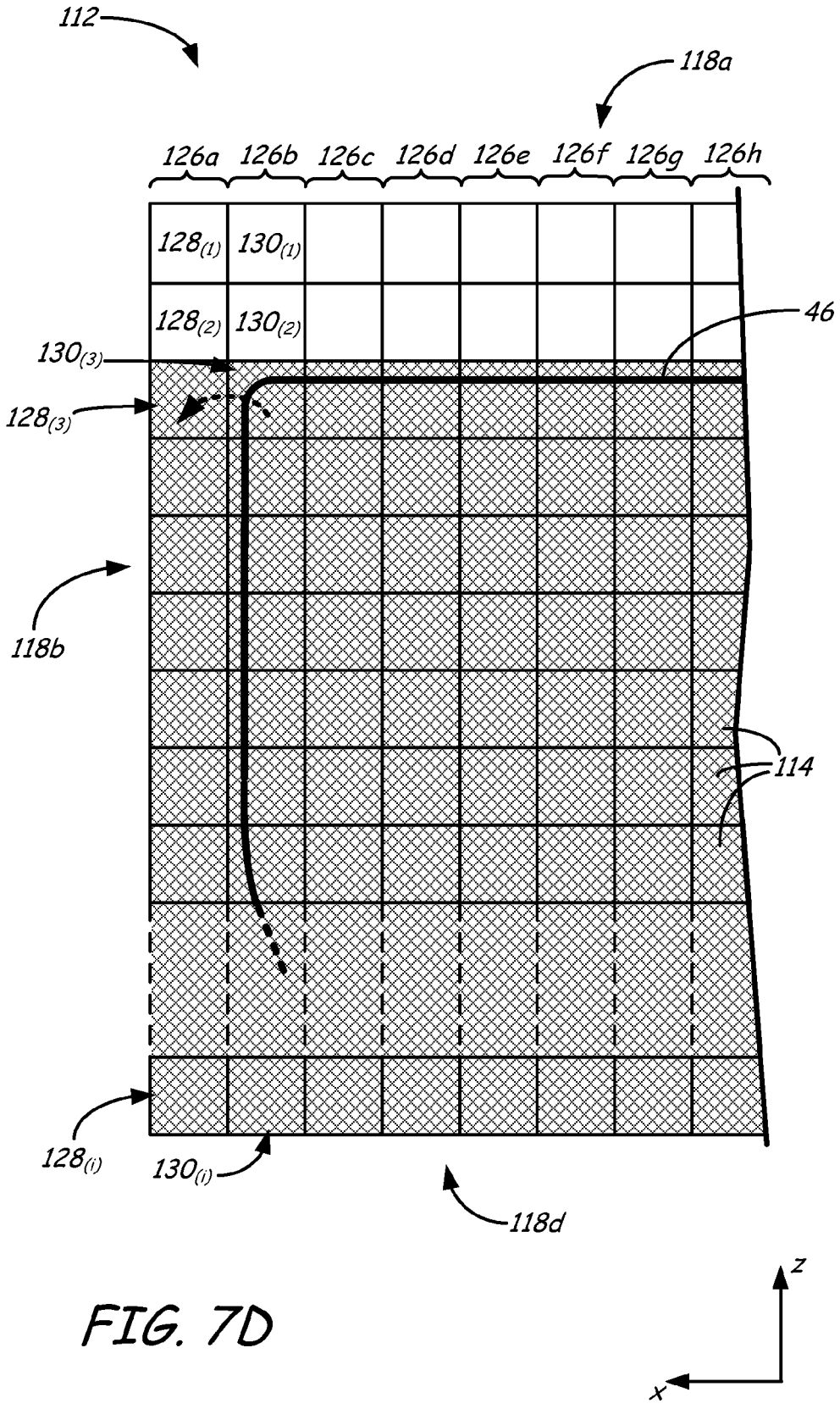

112
118a
126a
126b
126c
126d
126e
126f
126g
126h
128(1)
130(1)
128(2)
130(2)
46
130(3)
128(3)
118b
114
128(i)
130(i)
118d
z
x

FIG. 7D

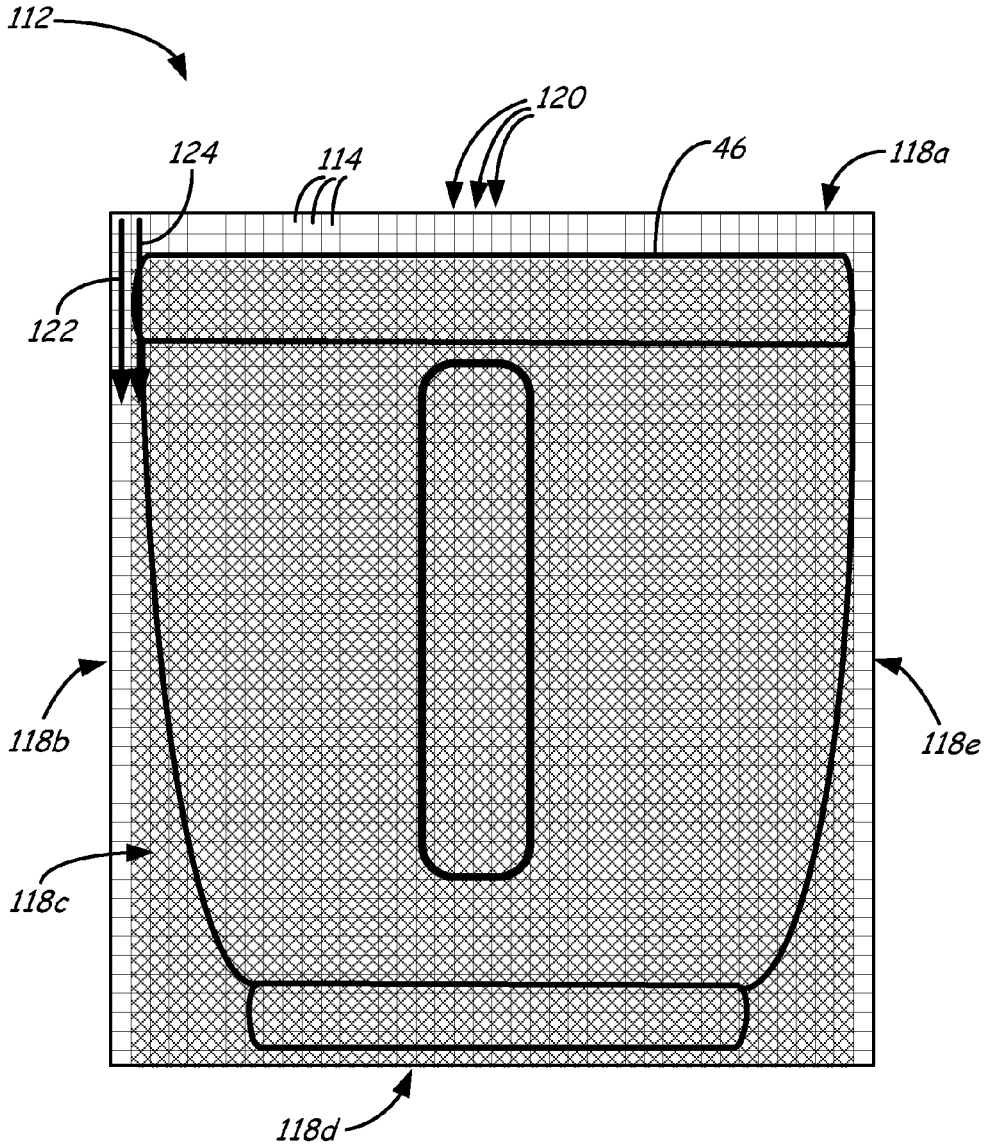
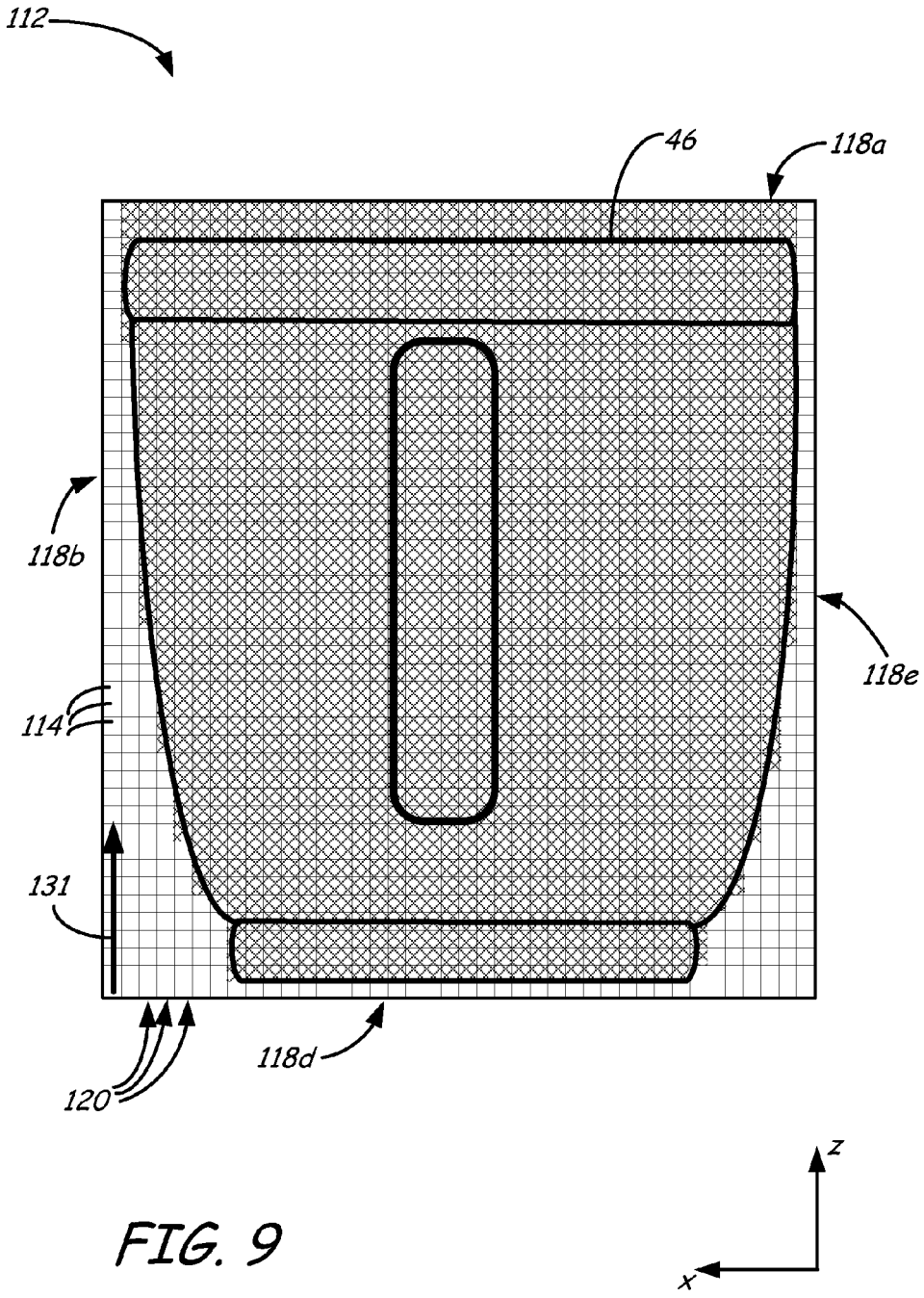


FIG. 8



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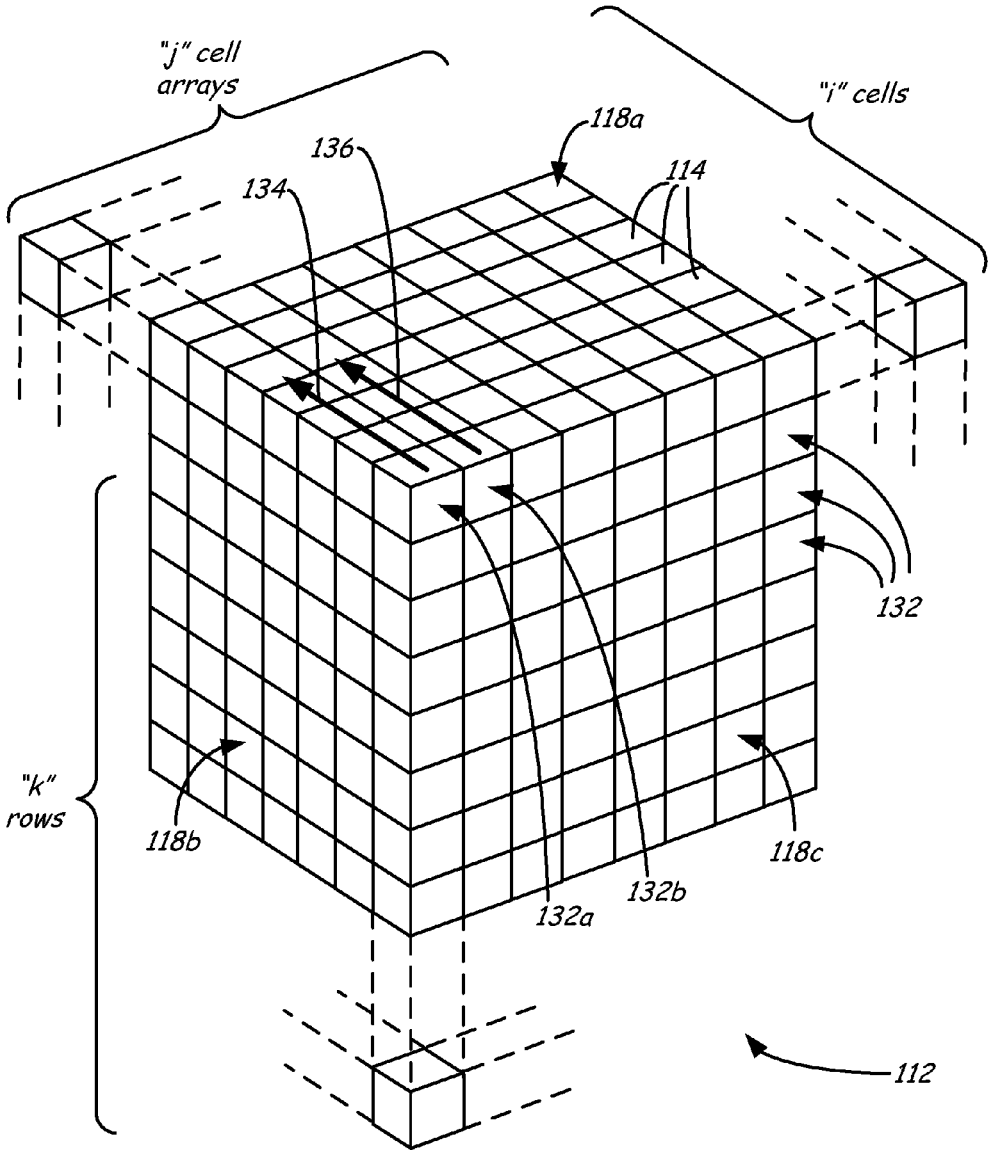
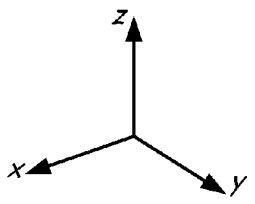

"j" cell arrays
"i" cells
118a
136
134
114
132
"k" rows
118b
118c
132a
132b
112

FIG. 10


z
x
y

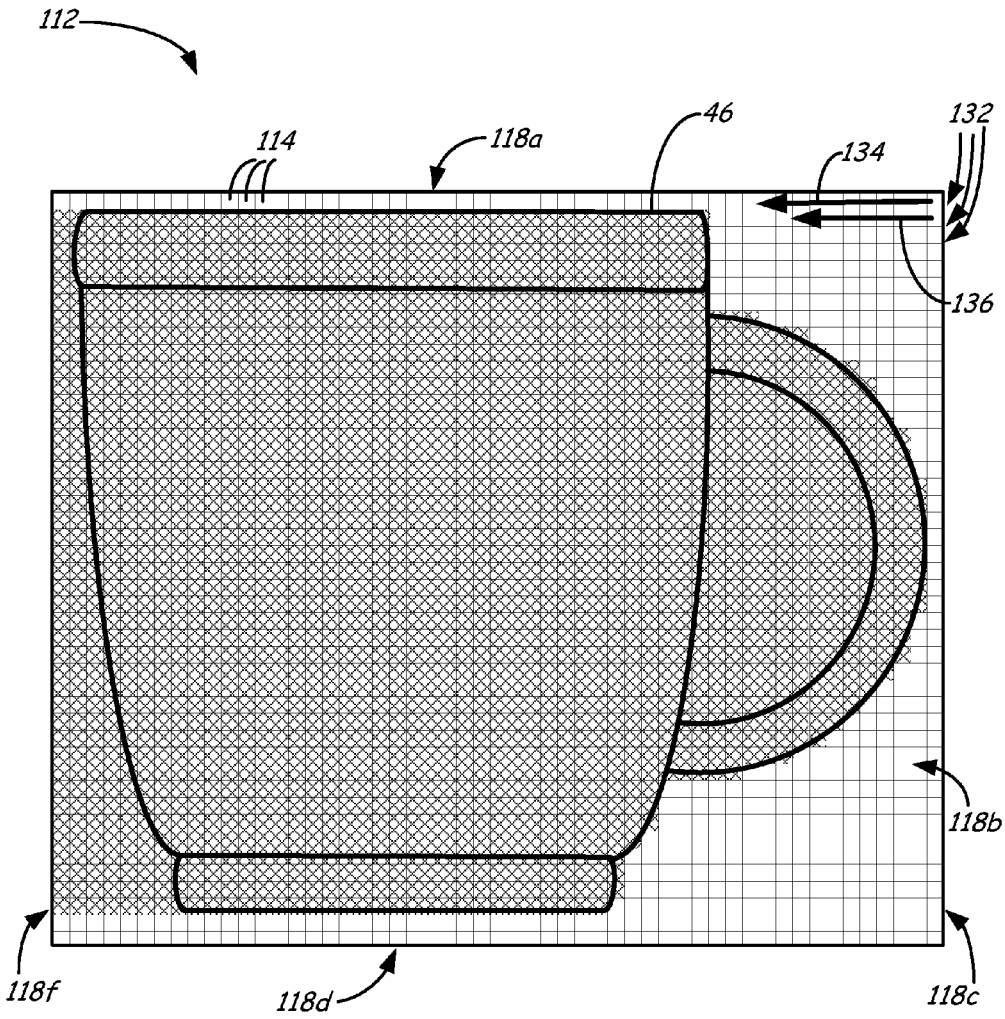


FIG. 11

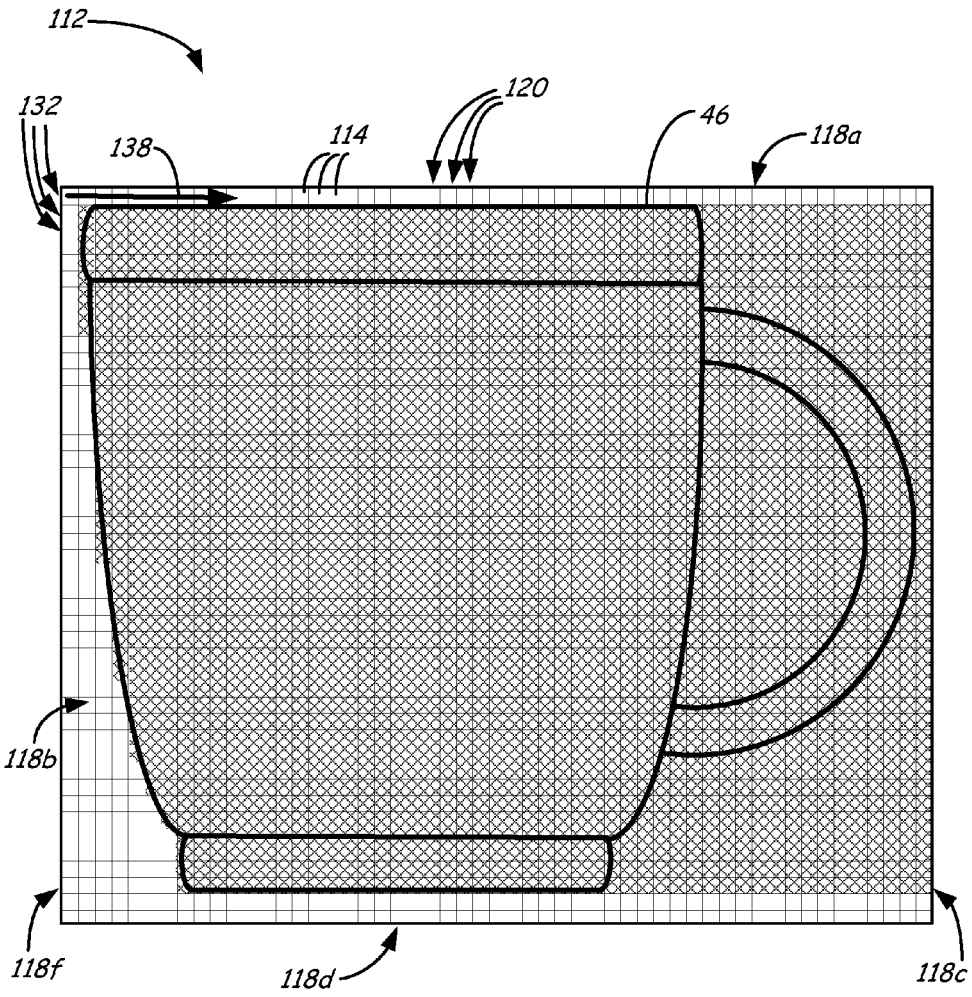
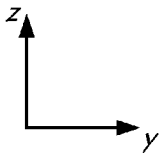


FIG. 12



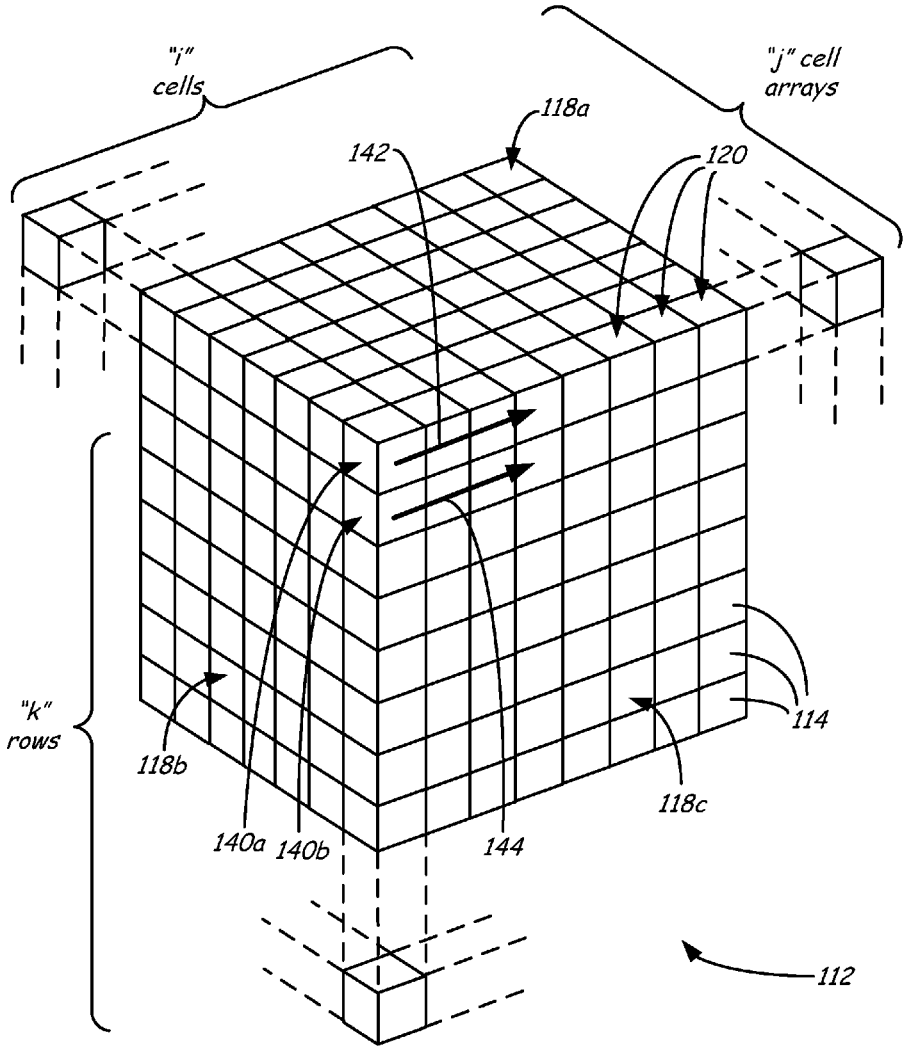

"i" cells
"j" cell arrays
118a
142
120
"k" rows
118b
140a
140b
144
118c
114
112
z
x
y

FIG. 13

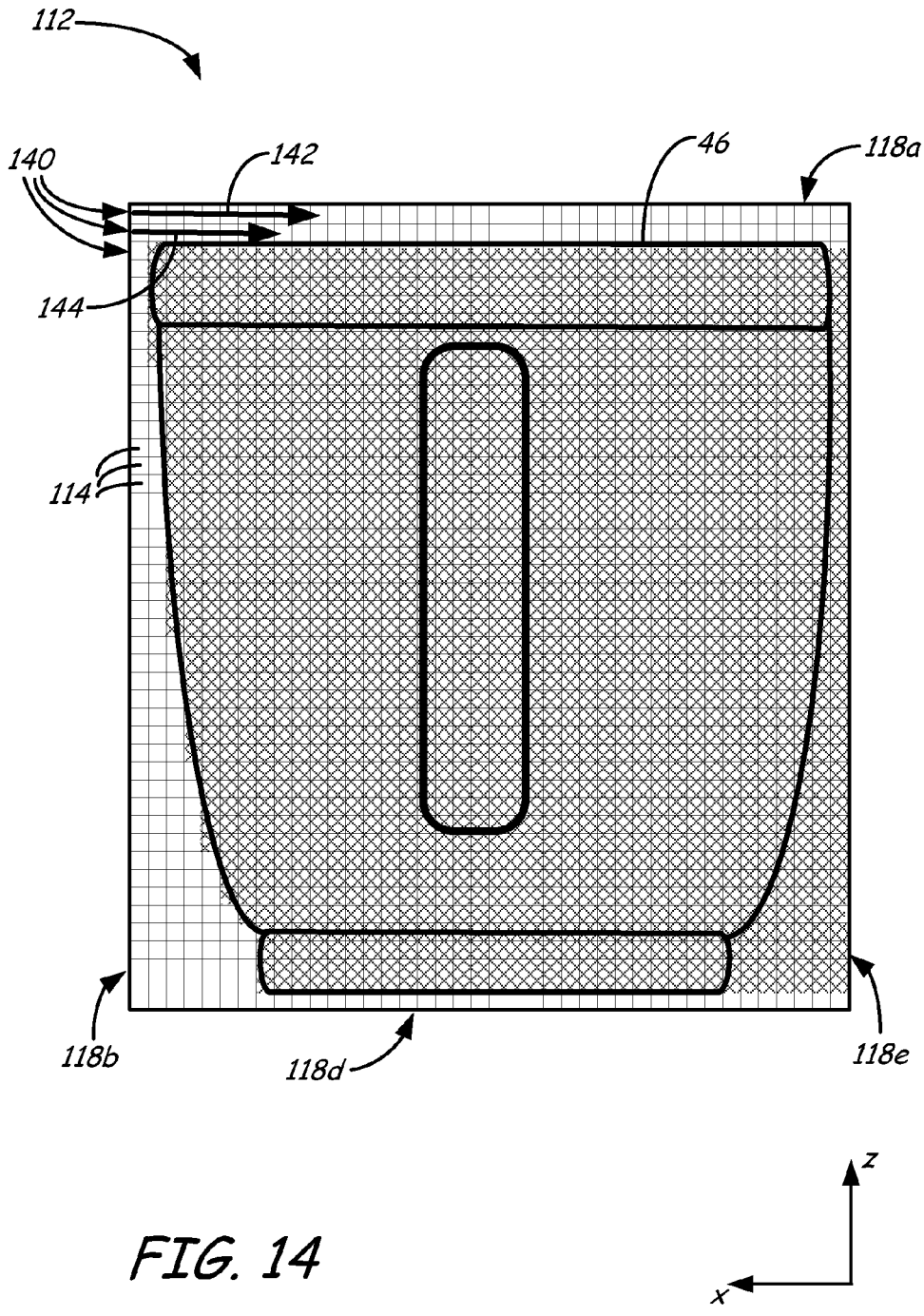


FIG. 14

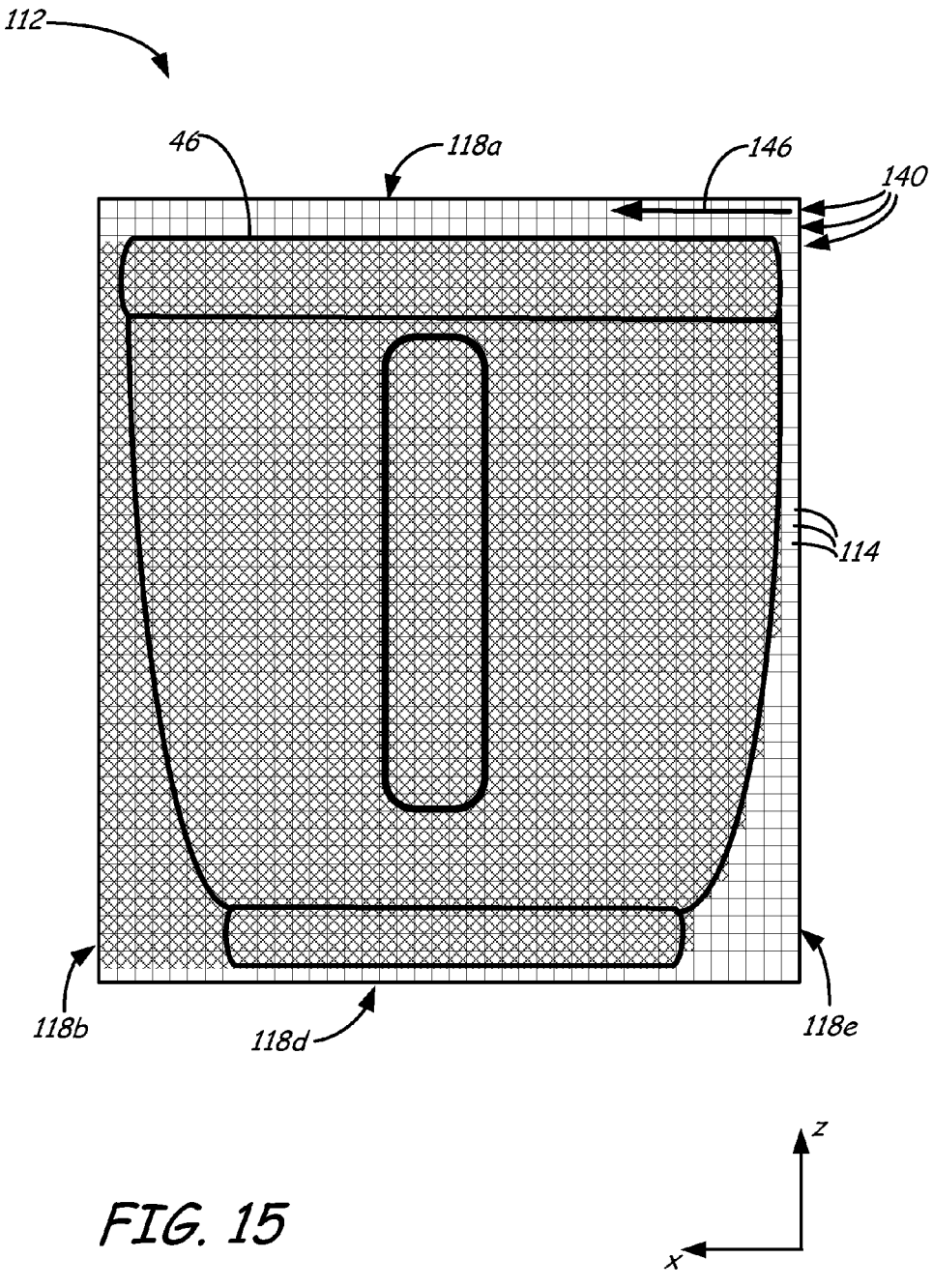


FIG. 15

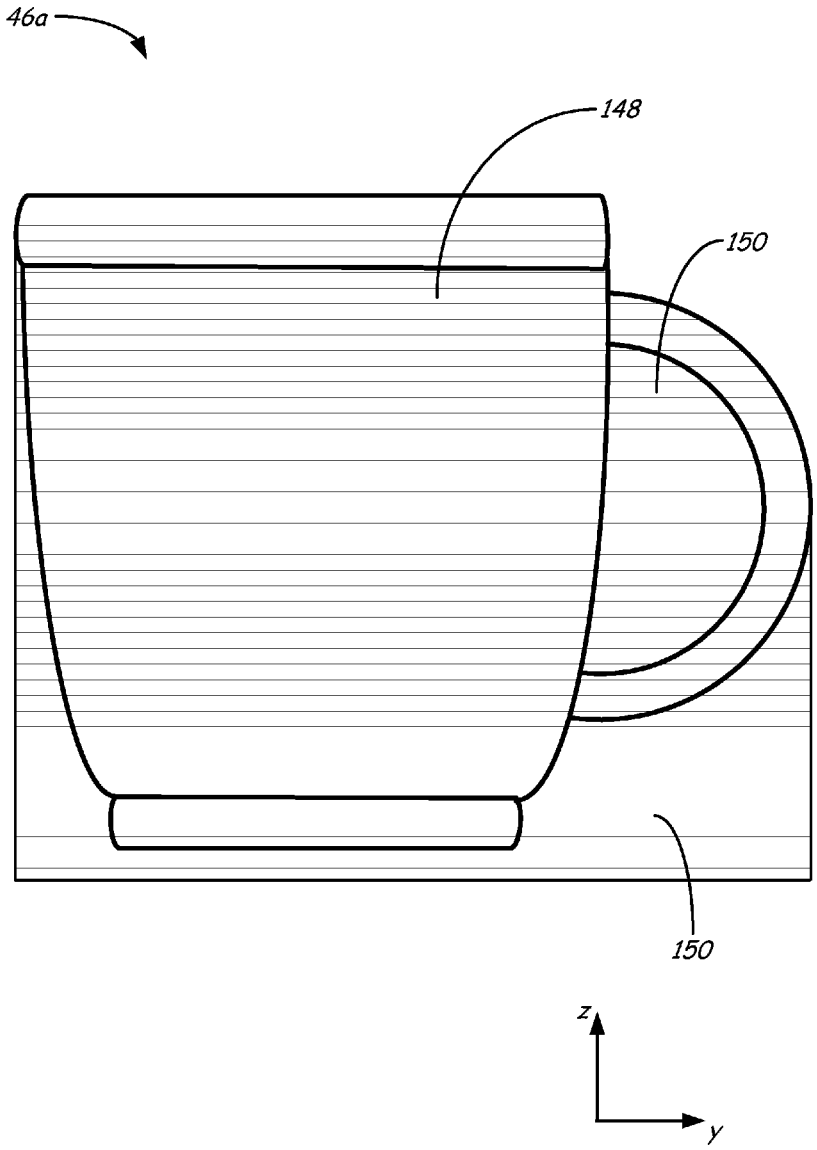
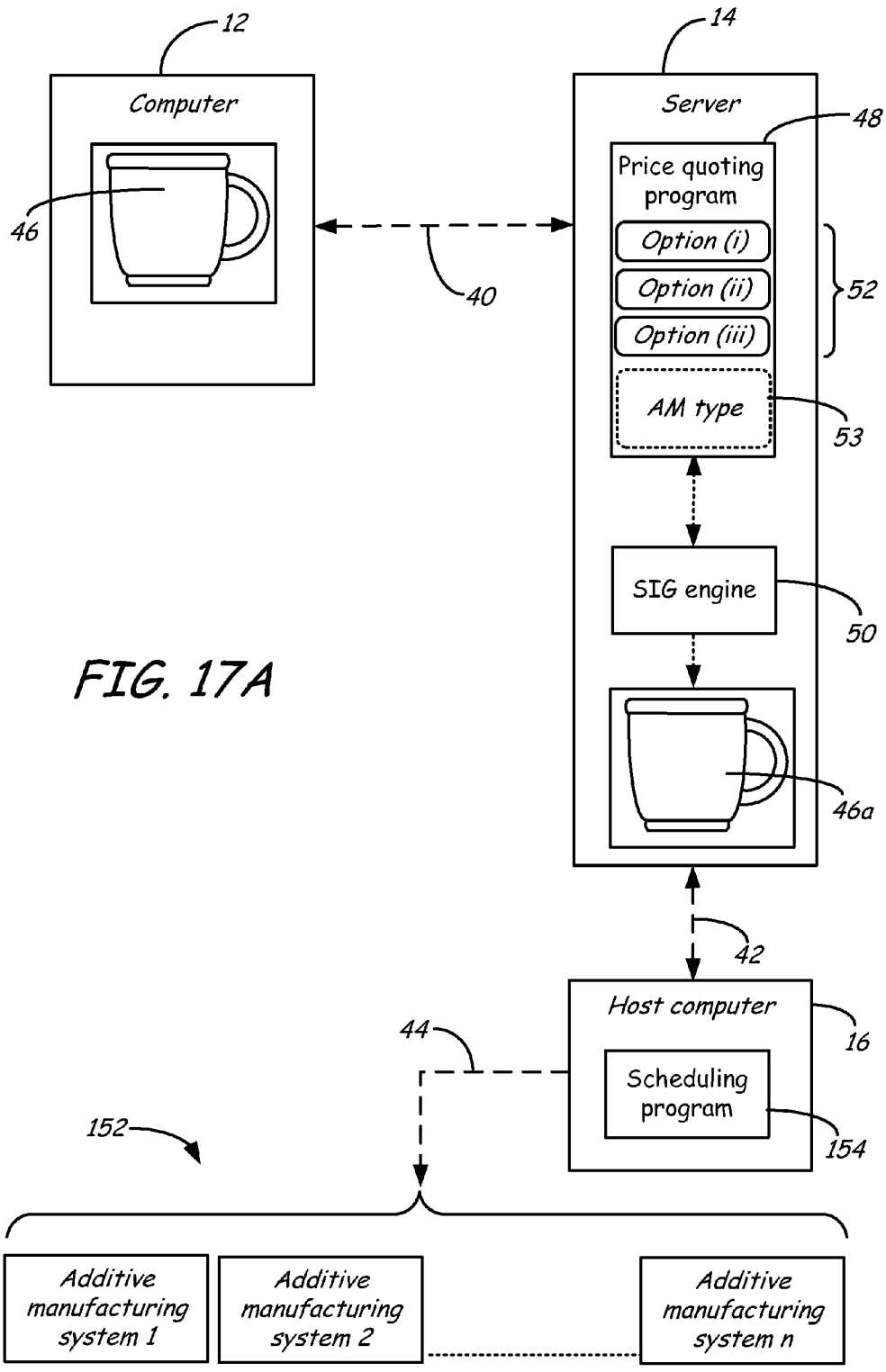


FIG. 16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Option (ii)
Option (iii)
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AM type
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SIG engine
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46a
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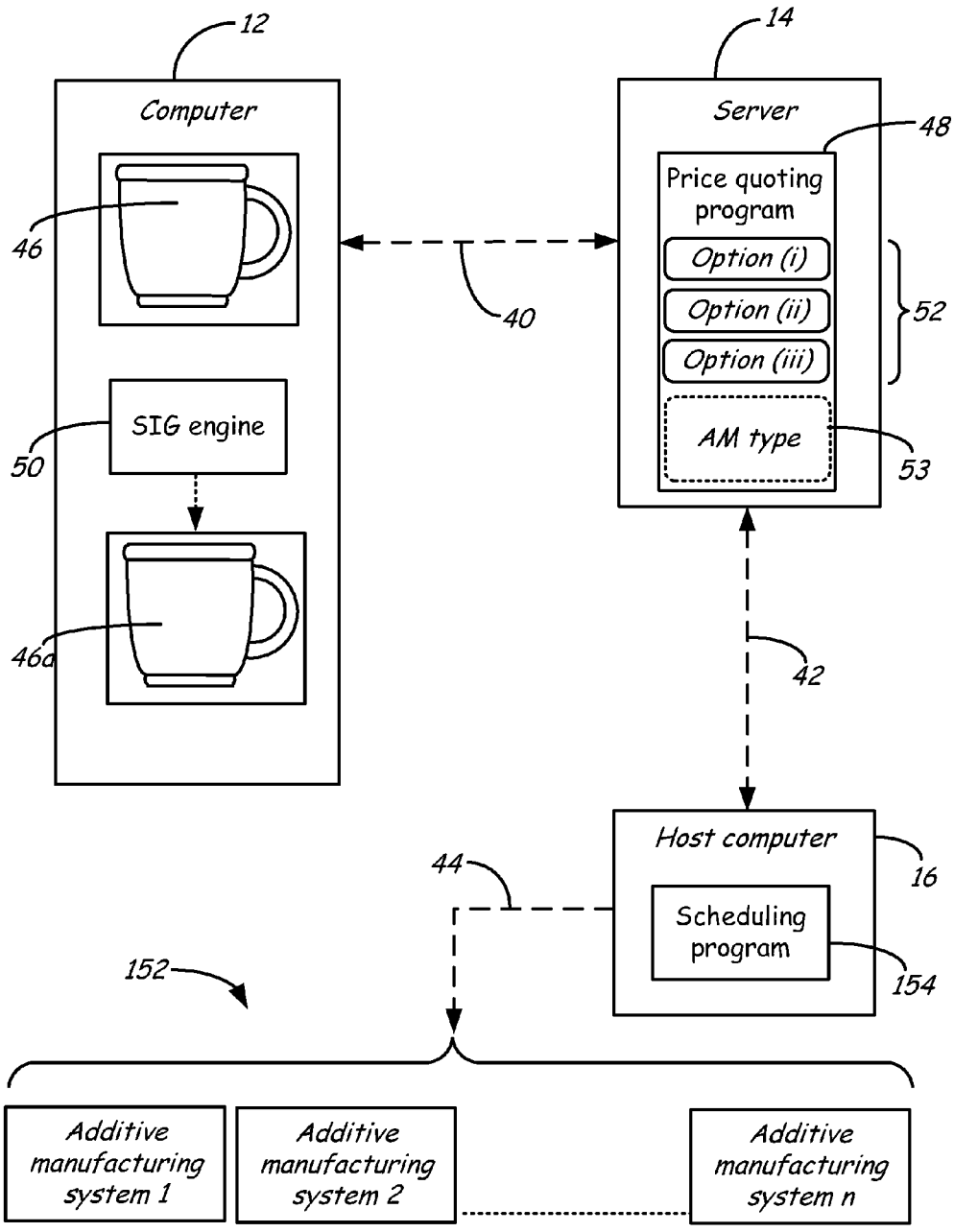
Host computer
16
44
Scheduling program
154
152
Additive manufacturing system 1
Additive manufacturing system 2
Additive manufacturing system n

FIG. 17A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46a
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Server
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Price quoting program
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Option (ii)
Option (iii)
52
AM type
53
40
42
Host computer
16
44
Scheduling program
154
152
Additive manufacturing system 1
Additive manufacturing system 2
Additive manufacturing system n

FIG. 17B

SOLID IDENTIFICATION GRID ENGINE FOR CALCULATING SUPPORT MATERIAL VOLUMES, AND METHODS OF USE

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a Continuation Application of U.S. patent application Ser. No. 13/231,533, filed Sep. 13, 2011; the contents of which are incorporated by reference.

BACKGROUND

The present disclosure relates to additive manufacturing processes for printing three-dimensional (3D) parts and support structures. In particular, the present disclosure relates to processes for calculating support material volumes for use in printing 3D parts and support structures with additive manufacturing techniques.

Additive manufacturing systems are used to print or otherwise build 3D parts from digital representations of the 3D parts (e.g., AMF and STL format files) using one or more additive manufacturing techniques. Examples of commercially available additive manufacturing techniques include extrusion-based techniques, jetting, selective laser sintering, powder/binder jetting, electron-beam melting, and stereolithographic processes. For each of these techniques, the digital representation of the 3D part is initially sliced into multiple horizontal layers. For each sliced layer, a tool path is then generated, which provides instructions for the particular additive manufacturing system to print the given layer.

For example, in an extrusion-based additive manufacturing system, a 3D part may be printed from a digital representation of the 3D part in a layer-by-layer manner by extruding a flowable part material. The part material is extruded through an extrusion tip carried by a print head of the system, and is deposited as a sequence of roads on a substrate in an x-y plane. The extruded part material fuses to previously deposited part material, and solidifies upon a drop in temperature. The position of the print head relative to the substrate is then incremented along a z-axis (perpendicular to the x-y plane), and the process is then repeated to form a 3D part resembling the digital representation.

In fabricating 3D parts by depositing layers of a part material, supporting layers or structures are typically built underneath overhanging portions or in cavities of 3D parts under construction, which are not supported by the part material itself. A support structure may be built utilizing the same deposition techniques by which the part material is deposited. The host computer generates additional geometry acting as a support structure for the overhanging or free-space segments of the 3D part being formed. Support material is then deposited from a second nozzle pursuant to the generated geometry during the printing process. The support material adheres to the part material during fabrication, and is removable from the completed 3D part when the printing process is complete.

SUMMARY

An aspect of the present disclosure is directed to a method for calculating a support material volume with a computer-based system. The method includes providing a tree data structure for a digital part, and generating a grid of cells for the tree data structure with the computer-based system, where the cells define a plurality of cell arrays. The method also includes pinging the cells of one of the cell arrays until a cell containing a subset of the tree data structure is reached or until each cell in the cell array is pinged, where if a cell containing the subset of the tree data structure is reached, then designating the reached cell and all remaining unpinged cells in the cell array as filled. The method further includes repeating the pinging step for each remaining cell array to determine a total filled volume, and subtracting a volume of the digital part from the total filled volume to determine a support material volume.

Another aspect of the present disclosure is directed to a method for manipulating a digital part with a computer-based system for use in an additive manufacturing process. The method includes (a) providing a grid of cells for a tree data structure of a digital part, where the cells are organized in cell arrays along a plurality of directional axes. The method also includes (b) selecting a first directional axis of the plurality of directional axes, (c) for each cell array along the first directional axis, pinging the cells of the cell array until a cell containing a subset of the tree data structure is reached, and (c) designating the reached cell and all remaining unpinged cells in the cell array as filled. The method further includes (d) repeating the steps (c) and (d) for each cell array along the remaining directional axes of the plurality of directional axes to determine a total filled volume for each of the plurality of directional axes, (e) subtracting a volume of the digital part from the total filled volume for each of the plurality of directional axes to determine a support material volume for each of the plurality of directional axes, and (h) identifying the directional axis having the lowest determined support material volume.

Another aspect of the present disclosure is directed to a price quoting method for use in an additive manufacturing process. The price quoting method includes providing a tree data structure for a digital part to be printed with the additive manufacturing process, and generating a grid of cells for the tree data structure with a computer-based system, where the cells of the grid define a plurality of cell arrays. For each cell array, the method also includes pinging the cells with the computer-based system until a cell containing a subset of the tree data structure is reached or until an end cell of the cell array is pinged. The method further includes designating all pinged cells containing subsets of the tree data structure and all unpinged cells as filled with the computer-based system, summing volumes of the designated filled cells with the computer-based system to provide a total filled volume, subtracting a volume of the digital part from the total filled volume with the computer-based system to determine a support material volume, and generating a price quote based at least in part on the determined support material volume.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a front schematic illustration of an additive manufacturing system in use with computer-based systems for printing 3D parts and support structures.

FIG. **2**A is a schematic illustration of the computer-based systems, illustrating a first embodiment in which a Solid Identification Grid engine of the present disclosure is retained on a server.

FIG. **2**B is a schematic illustration of the computer-based systems, illustrating a second embodiment in which a Solid Identification Grid engine of the present disclosure is retained on a remote computer.

FIG. **3** is a flow diagram of a method for using the Solid Identification Grid engine.

FIG. **4** is a flow diagram of a method of calculating a support material volume using the Solid Identification Grid engine.

FIG. **5** is a perspective view of a generated grid of cells using the Solid Identification Grid engine.

FIG. **6** is a perspective view of the generated grid of cells, illustrating a first set of cell arrays based on a first directional axis that is a positive direction along a z-axis.

FIGS. **7**A-**7**D illustrate a process for analyzing the first set of cell arrays, where FIG. **7**D illustrates an alternative process when supporting lateral surfaces of a 3D part.

FIG. **8** is a right side view of the grid of cells, depicting the first set of analyzed cell arrays.

FIG. **9** is a right side view of the grid of cells, depicting a second set of analyzed cell arrays based on a second directional axis that is a negative direction along the z-axis.

FIG. **10** is a perspective view of the generated grid of cells, illustrating a third set of cell arrays based on a third directional axis that is a positive direction along a y-axis.

FIG. **11** is a front view of the grid of cells, depicting the third set of analyzed cell arrays.

FIG. **12** is a front view of the grid of cells, depicting a fourth set of analyzed cell arrays based on a fourth directional axis that is a negative direction along the y-axis.

FIG. **13** is a perspective view of the generated grid of cells, illustrating a fifth set of cell arrays based on a fifth directional axis that is a positive direction along an x-axis.

FIG. **14** is a front view of the grid of cells, depicting the fifth set of analyzed cell arrays.

FIG. **15** is a front view of the grid of cells, depicting a sixth set of analyzed cell arrays based on a sixth directional axis that is a negative direction along the x-axis.

FIG. **16** is a front view of an oriented digital part with digital support layers, illustrating a slicing embodiment of the Solid Identification Grid engine.

FIG. **17**A is an alternative schematic illustration of the computer-based systems shown in FIG. **2**A, illustrating the computer-based systems in use with a farm of additive manufacturing systems and a scheduling program.

FIG. **17**B is an alternative schematic illustration of the computer-based systems shown in FIG. **2**B, illustrating the computer-based systems in use with a farm of additive manufacturing systems and a scheduling program.

DETAILED DESCRIPTION

The present disclosure is directed to a computer-implemented program, referred to as a Solid Identification Grid (SIG) engine, that quickly calculates the volume of support material needed to print or otherwise build a 3D part using an additive manufacturing system. The following discussion of the SIG engine is made in conjunction with a price quoting program that allows a user to request an online price quote for printing a 3D part. For instance, a developer may create a digital part (i.e., a digital representation of a 3D part) that he or she wishes to have printed as a physical 3D part by a manufacturer, such as by the on-demand service unit "REDEYE" of Stratasys, Inc., Eden Prairie, Minn. To accomplish this, the developer may access the manufacturer's price quoting program, which analyzes the developer's digital part and sends back a price quote for printing the physical 3D part.

The price quote is based on numerous factors, including the volumes of part and support materials required to print the 3D part. The required volume of part material is typically available based on the volume and geometry of the analyzed digital part. As such, the price quoting program can quickly determine the required part material volume, and its related cost.

The volume of support material, however, is more difficult to establish because the analyzed digital part does not include the support structure. Rather, layers of the support structure are typically generated at a later point in the process, during which the digital part is sliced into horizontal layers and tool paths are generated. As such, during the price quoting step, it is difficult to quickly establish the volume of support material needed to print the 3D part, and hence, its related cost.

The SIG engine of the present disclosure, however, is suitable for quickly calculating support material volumes need to print 3D parts. As discussed below, the SIG engine utilizes a collision detection technique to identify the geometry of a digital part. Based on the identified geometry, and the known volume of the digital part, the SIG engine can quickly calculate the volume of support material that will be necessary to print a support structure in coordination with the 3D part. Thus, the SIG engine is particularly suitable in combination with a price quoting program to provide instant price quotes. However, as discussed below, the SIG engine may also be used in conjunction with a variety of additional processes, such as tool-path generation processes, run-time and scheduling determinations, and the like.

FIG. **1** illustrates system **10** in use with computer **12**, server **14**, and host computer **16**, which depicts a suitable arrangement for implementing the SIG engine of the present disclosure in conjunction with a price quoting program. System **10** is an additive manufacturing system for printing or otherwise building 3D parts and support structures in a layer-by-layer manner.

Examples of suitable systems for system **10** include extrusion-based additive manufacturing systems, such as those commercially available by Stratasys, Inc., Eden Prairie, Minn. under the trademarks "FUSED DEPOSITION MODELING" and "FDM". In alternative embodiments, system **10** may be any suitable additive manufacturing system that prints or otherwise builds 3D parts in a layer-by-layer manner, and that relies on one or more materials to support overhanging and/or lateral surfaces of the 3D parts, such as jetting systems, selective laser sintering systems, powder/binder jetting systems, electron-beam melting systems, stereolithography systems, and the like.

System **10** includes build chamber **18**, z-axis gantry **19**, platen **20**, x-y-axis gantry **22**, print head **24**, and supply sources **26** and **28**. System **10** also includes controller **30**, which is one or more processor-based controllers configured to control the operation of the components of system **10**.

Build chamber **18** is an enclosable environment that contains platen **20** for printing a 3D part or model (referred to as 3D part **32**) and a corresponding support structure (referred to as support structure **34**) with part and support materials (e.g., thermoplastic materials). Build chamber **18** is desirably heated to reduce the rate at which the part and support materials solidify after being extruded and deposited (e.g., to reduce distortions and curling). In alternative embodiments, build chamber **18** may be omitted and/or replaced with different types of build environments. For example, 3D part **32** and support structure **34** may be printed in a build environment that is open to ambient conditions or may be enclosed with alternative structures (e.g., flexible curtains). The build environment may also be heatable in a variety of manners (e.g., with heated circulating air, heat lamps, and the like).

Z-axis gantry **19** is a vertical gantry assembly configured to move platen **20** along the vertical z-axis based on instructions provided from controller **30**. Platen **20** is a platform on which 3D part **32** and support structure **34** are printed in a layer-by-layer manner.

X-y-axis gantry **22** is a guide rail assembly that is configured to move print head **24** in a horizontal x-y plane based on instructions provided from controller **30**. The horizontal x-y plane is a plane defined by an x-axis and a y-axis (not shown in FIG. **1**), where the x-axis, the y-axis, and the z-axis are orthogonal to each other in a Cartesian coordinate system. In an alternative embodiment, platen **20** may be configured to move in the horizontal x-y plane within build chamber **18**, and print head **24** may be configured to move along the z-axis. Other similar arrangements may also be used such that one or both of platen **20** and print head **24** are moveable relative to each other. Furthermore, system **10** may be configured to print 3D part **32** and support structure **34** using different coordinate systems (e.g., a polar coordinate system, an oblique coordinate system, and the like).

Print head **24** is supported by x-y-axis gantry **22** for printing 3D part **32** and support structure **34** on platen **20** in a layer-by-layer manner, based on instructions provided from controller **30**. In the embodiment shown in FIG. **1**, print head **24** is a dual-tip extrusion head configured to deposit part and support materials from supply source **26** and supply source **28**, respectively.

Examples of suitable extrusion heads for print head **24** include those disclosed in Crump et al., U.S. Pat. No. 5,503,785; Swanson et al., U.S. Pat. No. 6,004,124; LaBossiere, et al., U.S. Pat. No. 7,604,470; Leavitt, U.S. Pat. No. 7,625,200; and Swanson et al., U.S. Pat. No. 8,419,996. In alternative embodiments, print head **24** may function as a multiple-stage screw pump, as disclosed in Batchelder et al., U.S. Pat. No. 5,764,521; and Skubic et al., U.S. Pat. No. 7,891,964. Furthermore, system **10** may include a plurality of print heads **24** for depositing part and/or support materials from one or more tips.

The part material is supplied to print head **24** from supply source **26** via feed line **36**, thereby allowing print head **24** to deposit the part material to print 3D part **32**. Correspondingly, the support material is supplied to print head **24** from supply source **28** via feed line **38**, thereby allowing print head **24** to deposit the support material to print support structure **34**.

The part and support materials may be provided to system **10** in a variety of different media. Commonly, the materials may be supplied in the forms of continuous filaments. For example, in system **10**, the part and support materials may be provided as continuous filament strands fed respectively from supply sources **26** and **28**, as disclosed in Swanson et al., U.S. Pat. No. 6,923,634; Comb et al., U.S. Pat. No. 7,122,246; Taatjes et al, U.S. Patent Application Publication Nos. 2010/0096485 and 2010/0096489; and Swanson et al., U.S. Patent Application Publication No. 2010/0283172. Examples of suitable average diameters for the filament strands of the modeling and support materials range from about 1.27 millimeters (about 0.050 inches) to about 3.0 millimeters (about 0.120 inches).

Alternatively, the part and support materials may exhibit non-cylindrical filament geometries, such as rectangular geometries. Examples of suitable dimensions for the exhibit non-cylindrical filament geometries include those disclosed in Batchelder et al., U.S. Patent Application Publication No. 2011,0076496. In further alternative embodiments, the part and support materials may be provided as other forms of media (e.g., pellets, slugs, and resins) from other types of storage and delivery components (e.g., supply hoppers and vessels).

During a printing operation, print head **24** deposits the received part and support materials onto platen **20** to print 3D part **32** and support structure **34** in a layer-by-layer manner based on instructions from controller **30**. Support structure **34** is desirably deposited to provide vertical support along the z-axis for overhanging regions of the layers of 3D part **32**, and, optionally, to provide lateral support to various surfaces of 3D part **32**. The use of support structure **34** thereby allows 3D part **32** to be built with a variety of geometries.

After the printing operation is complete, the resulting 3D part **32**/support structure **34** may be removed from build chamber **18**. Support structure **34** may then be removed from 3D part **32**, and 3D part **32** may undergo one or more post-printing operations (e.g., vapor smoothing and media blasting).

As can be appreciated, support structures (e.g., support structure **34**) are necessary to support overhanging portions and/or lateral surfaces of 3D parts (e.g., 3D part **32**) during the printing operation, which are not supported by the part material itself. Thus, the cost to print 3D part **32** is dependent on the volume of support material needed to print support structure **34** in a manner that sufficiently supports the layers of 3D part **32**. As a result, a price quoting program implemented by computer **12** and/or server **14** needs to account for this required support material volume when generating price quotes.

Computer **12**, server **14**, and host computer **16** are each one or more computer-based systems configured to communicate with each other and/or system **10**. Computer **12** may be any suitable computer-based system (e.g., a personal computer, laptop computer, server-based system, mobile device, computer tablet device, and the like), and is configured to communicate with server **14** over one or more network communication lines (referred to collectively as network line **40**).

Server **14** may be managed by a manufacturer that operates system **10**, and is configured to run a price quoting program that is accessible by multiple computers over network line **40**. For example, a user of computer **12** may communicate with server **14** over network line **40** to generate online price quotes for printing 3D parts, such as 3D part **32**. Server **14** is also configured to communicate with host computer **16** over one or more communication lines (referred to collectively as communication line **42**). Host computer **16** may also be managed by the manufacturer that operates system **10**, and is configured to communicate with system **10** over one or more communication lines (referred to collectively as communication line **44**) for printing 3D parts and support structures (e.g., 3D part **32** and support structure **34**).

As shown in FIG. **2**A, prior to the printing operation, a user may retain a digital representation (e.g., an AMF or STL format file) of 3D part **32**, referred to as digital part **46**, on one or more data storage devices of computer **12**. The manufacturer may correspondingly retain price quoting program **48** and SIG engine **50** on one or more data storage devices of server **14**. Price quoting program **48** is a computer-implement program accessible over the Internet that generates price quotes for printing 3D parts with system **10** or other additive manufacturing systems. SIG engine **50** is the computer-implemented program of the present disclosure, which calculates the volumes of support material that

are needed to print the 3D parts, as discussed below, and operates in conjunction with price quoting program **48**.

To request a price quote for printing 3D part **32** based on digital part **46**, the user of computer **12** may access price quoting program **48** over network line **40**. In the shown embodiment, the user of computer **12** also sends a copy of digital part **46** and any related specifications (e.g., part materials, dimensions, user-selected options, and the like) over network line **40** to server **14**.

The volume of support material needed to print 3D part **32** depends on the orientation of digital part **46** in the x-y-z coordinate system (or other coordinate system). As such, price quoting program **48** may include menu **52** of user-selectable options, where the user-selectable options can affect the orientation of digital part **46** during the printing operation. For example, menu **52** may include options such as (i) optimizing the price quote by orienting digital part **46** in a manner that minimizes the required volume of support material, (ii) preserving the orientation of digital part **46**, and (iii) orienting digital part **46** to minimize the z-axis height of 3D part **32**. In some embodiments, menu **52** (or other interface) may also include additional user-selectable options.

These user-selectable options may then be exported to SIG engine **50** when calculating the required support material volume. For example, option (i) allows SIG engine **50** to orient digital part **46** in any manner needed to minimize the amount of support material required to print 3D part **32**. As such, under option (i), SIG engine **50** can calculate the needed support material volume along multiple directional axes of digital part **46** to attain the directional axis that provides the lowest amount of required support material.

In comparison, options (ii) and (iii) limit the extent that digital part **46** can be reoriented from its initial orientation. As such, these two options may not necessary result in the lowest amount of support material, and consequentially, the lowest price quote. However, in many situations, users may prefer the 3D parts to be printed in particular orientations regardless of the cost effects, such as to preserve the strengths and/or aesthetic qualities of the 3D parts along particular surfaces.

Furthermore, price quoting program **48** may include menu **53**, which allows the user to select which additive manufacturing process to use to print or otherwise build 3D part **32**. As discussed below, the various types of additive manufacturing processes may require different volumes of support material to print or otherwise build 3D parts. For example, extrusion-based additive manufacturing systems typically only require support material to be placed below the part materials layers. In comparison, however, some jetting systems require support materials to also be used to support lateral surfaces of the 3D parts. Moreover, some powder-based additive manufacturing systems may recycle portions of the non-bound powders, thereby reducing the overall consumed volume of the support material. Accordingly, SIG engine **50** may be configured to calculate the support material volumes differently depending on the additive manufacturing process selected with menu **53**.

Upon receipt of digital part **46**, SIG engine **50** may extract information from price quoting program **48** (e.g., the user-selected options from menus **52** and **53**), and may analyze the received digital part **46** to calculate the volume of support material required to print 3D part **32**, as discussed below. SIG engine **50** may then output the calculated support material volume to price quoting program **48**, allowing price quoting program **48** to generate a price quote for printing 3D part **32** with system **10**. SIG engine **50** may also export a new digital part (referred to as new digital part **46***a*) to server **14**, where the new digital part **46***a* is the reoriented digital part **46**. Server **14** may then send the generated price quote and the new digital part **46***a* back to computer **12** over network line **40**.

If the user accepts the price quote, server **14** may then send the new digital part **46***a* to host computer **16** over communication line **42**. Host computer **16** may then slice digital part **46***a* into multiple horizontal layers, and generate digital support layers for support structure **34**. Host computer **16** may also generate tool-path instructions and other related information for each layer of digital part **46***a* and the digital support layers, and the resulting data may be transmitted to system **10** over communication line **44**. System **10** may then print 3D part **32** and support structure **34** based on the received data, where the volume of support material consumed to print support structure **34** corresponds to the volume of support material calculated by SIG engine **50**.

FIG. **2**B illustrates an alternative embodiment in which SIG engine **50** is retained on computer **12**. In this example, the user of computer **12** may install or otherwise copy an executable file of SIG engine **50** from server **14** (e.g., as a plug-in, widget, application, or the like). To request a price quote for printing 3D part **32** based on digital part **46**, the user of remote computer **14** may access price quoting program **48** over network line **40**. However, in this embodiment, digital part **46** is not immediately transmitted to server **14**.

Instead, SIG engine **50** analyzes digital part **46** on computer **12** to calculate the volume of support material required to print 3D part **32**. SIG engine **50** may then output the calculated support material volume to price quoting program **48** on server **14** over network line **40**. SIG engine **50** may also export the new digital part **46***a* to computer **12**. Upon receipt of the calculated support material volume, price quoting program **48** may generate a price quote for printing 3D part **32** from digital part **46***a*. Server **14** then sends the generated price quote back to computer **12** over network line **40**.

Retaining SIG engine **50** on computer **12** provides several advantages over having it retained on server **14**. First, digital part **46** is not required to be transmitted to sever **14** to attain price quotes, which can speed up the price quoting operation by eliminating this transfer step. Additionally, leaving digital part **46** on computer **12** during the price quote operation also allows the user of computer **12** to check price quotes on digital part **46** without apprehension of having a copy of digital part **46** being saved at a separate location outside of his or her control until he or she accepts the price quote.

If the user accepts the price quote sent from server **14**, a copy of digital part **46***a* and any specifications are then transmitted over network line **40** to server **14**. Server **14** may then send the copy of digital part **46***a* to host computer **16** over communication line **42**. Host computer **16** and system **10** may then be used to print 3D part **32** and support structure **34**, as discussed above.

The embodiments shown in FIGS. **2**A and **2**B illustrate suitable architectures for performing price quote operations with the use of SIG engine **50**. In a further suitable embodiment, price quote engine **48** may also function as a downloadable program that resides on computer **12**, and communicates with server **14** over network line **40**.

FIG. **3** illustrates a suitable method (referred to as method **54**) for implementing SIG engine **50** with a computer-based system (e.g., computer **12** and/or server **14**). The following discussion of method **54** is made with reference to system **10**, computer **12**, 3D part **32**, support structure **34**, and

digital part **46**. However, the operation of SIG engine **50** pursuant to method **54** may be used with a variety of additive manufacturing systems and computer-based systems in combination with 3D parts and support structures having numerous different geometries. An application of method **54** to analyze digital part **46** is also illustrated below in FIGS. **5-15**.

As shown in FIG. **3**, method **54** includes steps **56-74**, and initially involves running or otherwise loading SIG engine **50** to the memory of computer **12** (step **56**). Computer **12** may also load digital part **46** and/or information related to digital part **46**, such as x-y-z coordinate locations, surface area, triangle complexity, solid volume, the user-selected options from menus **52** and **53**, and the like. Computer **12** may also perform one or more error-check operations to check digital part **46** for errors. If errors are found, computer **12** may attempt to correct the errors and/or stop the operation of SIG engine **50** and inform the user of the errors.

After digital part **46** is loaded, computer **12** generates a tree data structure for digital part **46** by partitioning the geometry of digital part **46** into multiple subsets (step **58**). Examples of suitable tree data structures for use with SIG engine **50** include binary space partitioning (BSP) trees, octrees, and the like. For instance, with a BSP tree, computer **12** may recursively partition digital part **46** into convex subsets until each subset becomes simple enough to be individually pinged by computer **12** using a collision detection technique.

Computer **12** may then generate a 3D grid of cells defining a volume bounding box for the tree data structure of digital part **46** (step **60**), where the cells of the 3D grid desirably correspond in size to the subsets of the tree data structure. As discussed below, this allows computer **12** to quickly ping each cell of the 3D grid to determine whether a portion of the tree data structure for digital part **46** resides in a given cell. It is noted that computer **12** does not actually generate a physical or graphical 3D grid of cells (unless desired). Rather, as discussed below, the cells are volumetric increments of coordinate locations retained in the memory of computer **12** for subsequent analysis of the tree data structure for digital part **46**.

In steps **62***a*-**62***c*, computer **12** refers to which option the user selected with menu **52**. If the user selected option (i) to optimize the price quote by orienting digital part **46** in any manner to minimize the required volume of support material (step **62***a*), SIG engine **50** may be configured to calculate the support material volume over six or more directional axes (step **64***a*). For example, SIG engine **50** may be configured to calculate the support material volume for each primary or major directional axis in the x-y-z coordinate system (i.e., positive and negative directions along the major x-y-z axes), providing six separate calculations. The number of directional axes may also differ depending on the particular coordinate system used, such as for a polar coordinate system or an oblique coordinate system.

Alternatively, if the user selected option (ii) to preserve the orientation of digital part **46** (step **62***b*), SIG engine **50** may be configured to calculate the support material volume along single directional axis, which is the positive direction along the vertical z-axis for the received orientation of digital part **46** (step **64***b*). On the other hand, if the user selected option (iii) to orient digital part **46** to minimize the z-axis height of 3D part **32** (step **62***c*), SIG engine **50** may be configured to calculate the support material volume along two directional axes (step **64***c*). In this situation, SIG engine **50** may identify an orientation of digital part **46** that minimizes the height of digital part **46**. The two directional axes are then the positive and negative vertical directions along the given orientation.

After determining the number of directional axes to analyze, computer **12** then uses SIG engine **50** to calculate the support material volume required to print 3D part **32** from digital part **46** for each directional axis, as discussed below (step **66**). Computer **12** then selects the directional axis that corresponds to the lowest calculated support material volume (step **68**), and may orient digital part **46** such that the selected axis becomes a positive direction along the vertical z-axis (i.e., an upward facing direction) (step **70**). This provides the proper orientation of digital part **46** (and 3D part **32**) to print support structure **34** with the minimum amount of support material. In one embodiment, if option (ii) was selected, in which the orientation of digital part **46** is preserved (step **62***c*), steps **68** and **70** of method **54** may be omitted, as illustrated by broken line **75**.

Computer **12** may then output the calculated support material volume to price quote engine **48** (step **72**), allowing price quote engine **48** to generate a price quote based in part on the calculated support material volume. Computer **12** may also export a new digital part **46***a* (e.g., an AMF or STL format file) from the oriented digital part **46** (step **74**). As also discussed above, this new digital part **46***a* may then be transmitted to host computer **16** for use in printing 3D part **32** with system **10**.

FIG. **4** illustrates method **76**, which is an example of a suitable method for calculating the support material volume required to print 3D part **32** from digital part **46**, pursuant to step **66** of method **54** (shown in FIG. **3**). An application of method **76** to analyze digital part **46** is also illustrated below in FIGS. **5-15**.

As shown in FIG. **4**, method **76** includes steps **78-108**, and initially involves selecting a first directional axis along which digital part **46** is oriented to perform the calculation (step **78**). Under user-selected options (i) and (ii), the first directional axis may be the positive direction along the vertical z-axis (i.e., the upward facing direction) for the received digital part **46**. Alternatively, under user-selected option (iii), the first directional axis may be the positive direction along an axis that minimizes the build height of digital part **46**. It is noted that digital part **46** does not actually need to be reoriented during step **78**, which can consume processing power of computer **12**. Rather, computer **12** recognizes the directional axes in the coordinate system relative to digital part **46**. In other words, computer **12** may switch which direction is the upward vertical direction for digital part **46** while performing method **76**.

As discussed above, pursuant to step **60** of method **54** (shown in FIG. **3**), computer **12** previously generated a 3D grid of cells for digital part **46**. For the first directional axis, the cells of the 3D grid are arranged in multiple cell arrays, where each array of cells extends along the first directional axis. This is illustrated below, for example, in FIGS. **6** and **7A-7D**.

Computer **12** identifies and proceeds to a first cell array of the multiple cell arrays along the first directional axis (step **80**), and identifies and proceeds to a first cell in the first cell array (step **82**). Computer **12** then pings the current cell using a collision detection technique to determine if a portion of the tree data structure for digital part **46** resides in the current cell (step **84**). In particular, computer **12** may execute a collision detection query against the tree data structure (e.g., BSP tree) of digital part **46** to determine whether a subset of the tree data structure of digital part **46** resides in the current cell. As used herein, the terms "ping",

"pinging", and the like, with reference to a cell, refer to the execution of a collision detection query against the tree data structure of a digital part to determine whether a subset of the tree data structure resides in the cell.

In one embodiment, to reduce processing requirements on computer **12**, the pinging of each cell under step **84** may be performed at a central coordinate point of the given cell. As mentioned above, the cells of the 3D grid are volumetric increments of x-y-z locations, rather than physical or graphical cells. In this embodiment, the x-y-z locations are located at the central coordinate points of the volumetric increments (i.e., at the volumetric centers of the cells). As such, pursuant to step **84** of method **76**, computer **12** may execute the collision detection query against the central coordinate point in the current cell to determine whether a subset of the tree data structure for digital part **46** resides in the current cell. In alternative embodiments, the pinging in each cell under step **84** may be performed at any suitable coordinate location within the volume of the given cell.

While this embodiment may result in small numbers of false-positive results and false-negative results since the pinging is performed at particular x-y-z coordinates (rather than over full volumetric increments), the small volumes of each of the cells render such results minor or negligible. Moreover, this embodiment can substantially reduce the processing requirements on computer **12**, allowing SIG engine **50** to quickly perform the steps of method **76** and rapidly return calculated support material volumes to price quoting program **48**.

At step **86** of method **76**, if the pinging does not hit a portion of digital part **46** (i.e., hit a subset of the tree data structure for digital part **46**) in the current cell, computer **12** then checks whether the current cell is the last cell in the current cell array (step **88**). If not, computer **12** proceeds to the next successive cell in the current cell array (step **90**) and repeat steps **84**, **86**, **88**, and **90** until a portion of digital part **46** residing in a given cell along the current cell array is reached (step **86**), or until each cell in the current cell array is pinged (step **88**).

If a portion of digital part **46** is hit in a cell during one of the pinging steps, computer **12** then designates the current cell (i.e., the cell in which the portion of digital part **46** is hit) and all remaining subsequent and unpinged cells in the current cell array as being "filled" (step **92**). This step distinguishes the cells that do not contain any part or support materials (non-filled cells), and the cells that contain part or support materials (filled cells). This step also stops all subsequent pingings for the current cell array, thereby reducing the processing requirements of computer **12**.

After the given cell(s) of the current cell array are designated as "filled", computer **12** checks whether the current cell array is the last cell array of the 3D grid along the current directional axis (step **94**). If not, computer **12** proceeds to the next cell array along the current directional axis (step **96**), and repeat steps **82-96** for each of the remaining cell arrays of the 3D grid along the current directional axis.

Alternatively, pursuant to step **88**, if the last cell in the current cell array is pinged and no hits are made during the pinging steps (i.e., the tree data structure for digital part **46** does not reside in any of the cells of the current cell array), computer **12** proceeds to the next cell array along the current directional axis (step **96**, as illustrated by a broken line **110** that does not intersect step **92**), and repeat steps **82-86** for each of the remaining cell arrays of the 3D grid along the current directional axis.

After the last cell array of the 3D grid along the current directional axis is analyzed (step **94**), computer **12** then sums the volumes of all of the cells previously designated as filled (step **98**). This provides the total filled volume for digital part **46** and the digital support layers. In an alternative embodiment, the summing operation in step **98** may be performed for each cell array during or after designation step **92**, in a cumulative manner. The resulting summed total filled volume will be the same in either embodiment.

After the summed total filled volume is obtained, the volume of digital part **46** may then be subtracted from the summed total filled volume to provide an initial volume of support material needed to print 3D part **32** with system **10** (step **100**). Alternatively, this subtracting step may also be performed for each cell array during or after designation step **92**, where the summed filled volume for each cell array may be reduce or otherwise offset by the volume of digital part **46** along the given cell array.

In the shown example, support structure **34** (shown in FIG. **1**) is illustrated with a dense fill, and extends vertically downward from all overhanging surfaces of 3D part **32**. In this situation, the initial volume of support material generated in step **100** of method **76** provides an accurate representation of the amount of support material needed to print 3D part **32**. However, the initial support material volume attained from step **100** may be modified (step **102**) to accommodate variations in printing styles, such as column support structures, sparse-fill support structures, and the like. In one embodiment, the initial support material volume attained from step **100** may be reduced based on the algorithm disclosed in Heide, U.S. Patent Application Publication No. 2011/0178621, which may generate the digital support layers having convex outer dimensions that reduce in size and complexity in a downward direction along the vertical z-axis.

After the support material volume for digital part **46** is calculated along the first directional axis, computer **12** may then check whether the current directional axis is the last directional axis to analyze (step **104**). Under user-selected option (i), SIG engine **50** is set up to analyze digital part **46** along six or more directional axes (from steps **62***a* and **64***a* of method **54**). Similarly, under user-selected option (iii), SIG engine **50** is set up to analyze digital part **46** along two directional axes (from steps **62***c* and **64***c* of method **54**). In these situations, computer **12** proceeds to the next directional axis (step **106**) and repeat steps **80-106** for each remaining directional axis.

As mentioned above, when proceeding to each successive directional axis, computer **12** desirably does not reorient digital part **46**, which can take up valuable processing power. Instead, computer **12** merely designates the selected directional axis as the new "upward" direction and repeats steps **80-106** for each new upward direction.

After the support material volume for digital part **46** is calculated along each directional axis (step **106**), computer **12** then proceeds to step **68** of method **54** (shown in FIG. **3**) (step **108**). As such, as mentioned above, computer **12** may then select the directional axis that corresponds to the lowest calculated support material volume (step **68** of method **54**), may orient digital part **46** such that the selected axis becomes a positive direction along the vertical z-axis (i.e., an upward facing direction) (step **70** of method **54**), may output the calculated support material volume to price quoting program **48** (step **72** of method **54**), and may export new digital part **46***a* (step **74** of method **54**).

Alternatively, under user-selected option (ii), SIG engine **50** is configured to analyze digital part **46** only along a single

directional axis (from steps **62***b* and **64***b* of method **54**). In this case, after steps **100** and **102** of method **76** are performed for the first and only directional axis, computer **12** may then proceed directly to step **68** of method **54** (step **108**), or alternatively, directly to step **72** of method **54** (as illustrated by broken line **75** in FIG. **3**). In this case, may output the calculated support material volume to price quoting program **48** (step **72** of method **54**), and, optionally, export new digital part **46***a* (step **74** of method **54**).

FIGS. **5-15** illustrate an application of method **54** (shown in FIG. **3**) and method **76** (shown in FIG. **4**) for calculating the support material volume required to print 3D part **32** from digital part **46**, based on user-selected option (i) from menu **52**. As shown in FIG. **5**, after steps **56** and **58** of method **54** are performed, computer **12** generates grid **112**, which is a 3D grid of cells **114** that define a volume bounding box for the tree data structure of digital part **46** (step **60** of method **54**).

As mentioned above, in step **60** of method **54**, computer **12** does not actually generate a physical or graphical grid **112** (unless desired). Rather, the x-y-z locations of the central coordinate points of cells **114** (or other selected coordinate locations within cells **114**) are retained in the memory of computer **12**.

For example, expanded cells **114***a*-**114***c* respectively include central coordinate points **116***a*-**116***c*, each of which are located at the centers of their respective cell **114***a*-**114***c*. In this example, in which cells **114** have the same volumes, central coordinate points **116***a* and **116***b* are offset from each other along the z-axis by a single increment. Similarly, central coordinate points **116***b* and **116***c* are offset from each other along the x-axis by the same single increment. Cells **114** aligned along the y-axis also have central coordinate points offset from each other by the same single increment.

Accordingly, SIG engine **50** may use a preset volume for cells **114** to reduce processing time when generating grid **112**. As shown, this positions the central coordinate points (e.g., points **116***a*-**116***c*) of cells **114** at the same preset increments from each other. In alternative embodiments, however, cells **114** may have different geometric shapes (e.g., rectangular, pyramidal, and the like) and/or may have different volumes from each other, which may affect the locations of the central coordinate points of the cells.

Furthermore, SIG engine **50** may provide a user option to select the desired volumes for cells **114**. In general, smaller volumes for cells **114** provide more accurate calculations, and vice versa. However, smaller volumes for cells **114** also increase the number of cells that define the volume bounding box for digital part **46**, thereby increasing the total number of cells that are pinged. This can increase the processing time required to perform the calculations.

As such, SIG engine **50** desirably operates with cell volumes that balance accuracy and processing time. Examples of suitable volumes for each cell **114** of grid **112** range from about 1×10^{-9} cubic inches (e.g., a cube having sides of about 0.001 inches) to about 0.001 cubic inches (e.g., a cube having sides of about 0.1 inches). In one embodiment, examples of suitable volumes for each cell **114** range from about 1.25×10^{-7} cubic inches (e.g., a cube having sides of about 0.005 inches) to about 1.25×10^{-4} cubic inches (e.g., a cube having sides of about 0.05 inches).

As further shown in FIG. **5**, grid **112** has six sides facing the major directional axes of the x-y-z coordinate system, namely top side **118***a* facing the positive direction along the z-axis, a bottom side (not shown in FIG. **5**) facing the negative direction along the z-axis, front side **118***b* facing the positive direction along the x-axis, a rear side (not shown in FIG. **5**) facing the negative direction along the x-axis, a right side **118***c* facing the positive direction along the y-axis, and a left side (not shown in FIG. **5**) facing the negative direction along the y-axis. The terms top, bottom, front, rear, right, and left are not intended to be limiting on any particular orientation, and are used herein merely for ease of discussion.

After grid **112** is generated, SIG engine **50** then calculates the volume of support material required to print 3D part **32** with system **10**, pursuant to step **66** of method **54**, and as described by method **76**. Accordingly, pursuant to step **78** of method **76**, computer **12** selects a first directional axis for performing the analysis. For convenience, the positive direction along the z-axis may be selected as the first directional axis to perform the analysis.

FIG. **6** further illustrates grid **112** and maintains the same orientation as shown in FIG. **5**. As shown in FIG. **6**, for the positive direction along the z-axis, cells **114** are arranged in multiple cell arrays, referred to as cell arrays **120**, each extending downward along the z-axis between top side **118***a* and the bottom side of grid **112** (not shown in FIG. **6**). Each cell array **120** includes "i" number of cells **114** along the z-axis. For ease of discussion, cell arrays **120** may be organized into rows aligned with the x-z plane. Grid **112** includes "j" number of cell arrays **120** per row, and "k" number of rows of cell arrays **120** along the y-axis, such that grid **112** includes a total number of j×k cell arrays **120**, and a total number of i×j×k cells **114**.

Pursuant to step **80** of method **76**, computer **12** may proceed to a first cell array **120**, which may located at any suitable location within grid **112**. For convenience, the first cell array **120** may be a corner cell array, such as cell array **120***a*, which is located in the first row at the corner of top side **118***a*, front side **118***b*, and right side **118***c*. Pursuant to steps **82-94** of method **76**, computer **12** then analyzes cells **114** in cell array **120***a* in a downward direction, as illustrated by arrow **122** (as discussed further below in FIGS. **7A-7D**).

After cell array **120***a* is analyzed, computer **12** then proceeds to the next cell array **120** (step **96**). In the current example, the next cell array **120** is the adjacent cell array **120** in the first row along the x-axis, referred to as cell array **120***b*. Pursuant to steps **82-94** of method **76**, computer **12** then analyzes cells **114** in cell array **120***a* in a downward direction, as illustrated by arrow **124** (as also discussed further below in FIGS. **7A-7D**). Computer **12** may then repeat steps **82-96** of method **76** for each successive cell array **120** in the current row.

When the first row of cell arrays **120** have been analyzed, computer **12** may then proceed to the first cell array **120** in the second row of cell arrays **120**, referred to as cell array **120***c* (step **96**). Computer **12** then repeats steps **82-96** for each cell array **120** in the second row, and for each remaining row of cell arrays **120** until all cell arrays **120** of grid **112** are analyzed. Analysis of cell arrays **120** in this row-based manner provides a convenient and organized way to proceed through steps **82-96** of method **76**. However, SIG engine **50** may alternatively be configured such that computer **12** analyzes cell arrays **120** in different orders, as desired.

FIG. **7A-7D** illustrate the application of steps **82-96** for a given row of cell arrays **120**, which includes cell arrays **126***a*-**126***h*, and also depict bottom side **118***d* of grid **112**. As shown in FIG. **7A**, pursuant to step **82** of method **76**, computer **12** may proceed to a first cell **114** in cell array **126***a*, referred to as cell $\mathbf{128}_{(1)}$. Computer **12** then pings cell $\mathbf{128}_{(1)}$ to determine whether a subset of the tree data structure for digital part **46** resides in cell $\mathbf{128}_{(1)}$ (step **84**).

In the shown example, the tree data structure for digital part **46** does not include any subsets in cell $\mathbf{128}_{(1)}$ (step **86**). As such, computer **12** then checks whether the cell $\mathbf{128}_{(1)}$ is the last cell **114** in cell array **126***a* (step **88**). Since cell array **126***a* contains additional cells **114**, computer **12** then proceeds to the next successive cell **114** in cell array **126***a* (step **90**). The next successive cell in cell array **126***a* from cell $\mathbf{128}_{(1)}$ is determined by proceeding from cell $\mathbf{128}_{(1)}$ to the next cell **114** along cell arrays **126***a* that is in an opposite direction from the directional axis selected in step **78**. In this case, the currently selected directional axis is the positive direction along the z-axis. As such, the next successive cell **114** in cell array **126***a* from cell $\mathbf{128}_{(1)}$ is located downward along the z-axis from cell $\mathbf{128}_{(1)}$ (i.e., in the negative direction along the z-axis, as illustrated by arrow **122**), and is referred to as cell $\mathbf{128}_{(2)}$.

Computer **12** then pings cell $\mathbf{128}_{(2)}$ to determine whether a subset of the tree data structure for digital part **46** resides in cell $\mathbf{128}_{(2)}$ (step **84**). In this case, the tree data structure for digital part **46** also does not include any subsets in cell $\mathbf{128}_{(2)}$ (step **86**). In fact, as shown, none of the cells **114** in cell array **126***a* include any subsets of the tree data structure for digital part **46**. As such, pursuant to steps **84-90** of method **76**, computer **12** may continue to ping each successive cell **114** downward along cell array **126***a* until the last cell **114** of cell array **126***a* located at bottom side **118***d* of grid **112** (referred to as cell $\mathbf{128}_{(i)}$ is pinged.

Since cell array **126***a* does not include any subsets of the tree data structure for digital part **46**, step **92** of method **76** is bypassed, and none of the cells **114** in cell array **126***a* are designated as "filled". Instead, computer **12** proceeds to the next cell array **120** (step **96**, as illustrated by broken line **110** in FIG. **4**), which is cell array **126***b*. Pursuant to step **82** of method **76**, computer **12** proceeds to a first cell **114** in cell array **126***b*, referred to as cell $\mathbf{130}_{(1)}$. Computer **12** then pings cell $\mathbf{130}_{(1)}$ to determine whether a subset of the tree data structure for digital part **46** resides in cell $\mathbf{130}_{(1)}$ (step **84**).

As this point, the tree data structure for digital part **46** also does not include any subsets in cell $\mathbf{130}_{(1)}$ (step **86**). As such, computer **12** performs steps **88** and **90** to proceed to the next subsequent cell **114** in cell array **126***b*, as illustrated by arrow **124**, which is cell $\mathbf{130}_{(2)}$. Computer **12** then repeats steps **84-90** for cell $\mathbf{130}_{(2)}$, which also does include any subsets of the tree data structure. Therefore, computer **12** performs steps **88** and **90** to proceed to the next successive cell **114** in cell array **126***b*, as further illustrated by arrow **124**, which is cell $\mathbf{130}_{(3)}$.

Computer **12** then pings cell $\mathbf{130}_{(3)}$ to determine whether a subset of the tree data structure for digital part **46** resides in cell $\mathbf{130}_{(3)}$ (step **84**). In this case, the tree data structure for digital part **46** does include a subset in cell $\mathbf{130}_{(3)}$ (step **86**). As such, computer **12** then designates the cell $\mathbf{130}_{(3)}$ and all remaining subsequent and unchecked cells **114** in cell array **126***b* down to cell $\mathbf{130}_{(i)}$ as being "filled" (step **92**).

This is illustrated in FIG. **7**B, in which cell $\mathbf{130}_{(3)}$ and all cells **114** in cell array **126***b* below cell $\mathbf{130}_{(3)}$, down to the last cell $\mathbf{130}_{(i)}$, are designated as "filled". This distinguishes the cells of cell array **126***b* that do not contain any part or support materials (non-filled cells), and the cells of cell array **126***b* that contain part or support materials (filled cells).

Computer **12** then proceeds to the next cell array **120** (step **96**), which is cell array **126***c*, and repeats steps **82-96** for each remaining cell array **120** of grid **112** (e.g., cell arrays **126***d*-**126***h*). This results in "filled" designation pattern shown in FIG. **7**C.

FIG. **7**D illustrates an alternative operation of SIG engine **50**. As mentioned above, SIG engine **50** may be configured to calculate the support material volumes differently depending on the additive manufacturing process selected with menu **53**. FIG. **7**D illustrates an embodiment in which support material is also required to support the lateral surfaces of 3D part **32**, such for use with some jetting-based additive manufacturing systems.

In this operation, based on the user-selected option with menu **53** of price quoting program **48**, when computer **12** designates cell $\mathbf{130}_{(3)}$ as "filled", pursuant to step **92** of method **76**, computer also increments one or more cell arrays **120** backwards and designates the respective cells **114** as filled. In the current example, cell array **126***a* is the only cell array that may be backtracked to. As such, computer **12** designates the adjacent cell **114** in cell array **126***a* (referred to as cell $\mathbf{128}_{(3)}$) as filled. Correspondingly, computer **12** also designates all cells **114** in cell array **126***a* below cell $\mathbf{128}_{(3)}$, down to the last cell $\mathbf{128}_{(i)}$, are designated as "filled". This accounts for support material that is printed to support the lateral surfaces of 3D part **32** when printing with additive manufacturing systems that requires such support structures.

In a further alternative embodiment, SIG engine **50** may be configured to perform ping jumps, where the pinging operation on a given cell array **120** may jump downward by a preset increment number of cells **114** until a subset of the tree structure for digital part **46** is reached. At that point, computer **12** may backtrack the pinging operation upward within a given jump increment to identify the surface of digital part **46**. This ping-jumping technique is suitable for reducing the time required to perform the pinging operations, and is particularly useful in regions of grid **112** that typically do not contain portions of 3D parts, such as in the corners of grid **112**.

FIG. **8** further illustrates the example shown in FIG. **7**C, where FIG. **8** is a front view of grid **112** after step **94** of method **76** is completed for the last cell array **120**, and depicts rear side **118***e*. At this point, computer **12** sums the volumes of cells **120** that are designated as filled (step **98**), which provides the total filled volume for digital part **46** and the digital support layers. As discussed above, the summing operation in step **94** may alternatively be performed after each designation step **92** in a cumulative manner.

Computer **12** then subtracts the volume of digital part **46** from the summed volume to provide an initial volume of support material needed to print 3D part **32** with system **10** (step **100**). Computer **12** may also modify the initial volume of support material to accommodate variations in printing styles, such as column support structures, sparse-fill support structures, and the like (step **102**). For example, when using a sparse-fill arrangement, computer **12** may reduce the initial volume of support material by a factor, such as by a preset factor to provide the calculated support material volume for digital part **46** along the positive direction of the z-axis.

Computer **12** then checks whether the positive direction of the z-axis is the last directional axis to analyze (step **104**). Under the user-selected option (i) from menu **52**, SIG engine **50** is configured to analyze digital part **46** along six or more directional axes (from steps **62***a* and **64***a* of method **54**). In this situation, computer **12** then proceeds to the next directional axis (step **106**) and repeats steps **80-106**.

As shown in FIG. **9**, the next directional axis may be the negative direction along the z-axis. In this case, the same cell arrays **120** are used, but are analyzed in an inverted manner compared to the previous operation shown in FIGS. **7**A-**7**D and **8**. In other words, the first cell **114** in each cell array **120** is located adjacent to bottom side **118***d*, and the last cell **114**

in each cell array **120** is located adjacent to top side **118***a*. Accordingly, for each cell array **120**, cells **114** are pinged upward during steps **84-92** of method **76**, as illustrated by arrow **131**.

When a given pinged cell **114** includes a subset of the tree data structure for digital part **46** (steps **84** and **86**), computer **12** then designates the pinged cell and all remaining subsequent and unchecked cells **114** in the current cell array **120**, upward toward the last cell **114**, as being "filled" (step **92**). Therefore, after computer **12** completes the analysis of steps **80-104**, the cells **114** designated as filled extend upward, as shown in FIG. **9**. The resulting calculated support material volume is then based on this upward arrangement, which corresponds to a situation in which digital part **46** is oriented such that the negative direction along the z-axis becomes the upward direction for printing 3D part **32**.

Computer **12** then checks whether the negative direction of the z-axis is the last directional axis to analyze (step **104**). Under the current situation, computer **12** may proceed to a next directional axis (step **106**) and repeat steps **80-106**. For example, the next directional axis may be the positive direction along the y-axis.

As shown in FIG. **10**, for the positive direction along the y-axis, cells **114** are arranged in multiple cell arrays, referred to as cell arrays **132** extending laterally along the y-axis between right side **118***c* and the left side of grid **112** (not shown in FIG. **10**). Each cell array **132** includes "i" number of cells **114** along the y-axis. For ease of discussion, cell arrays **132** may be organized into rows aligned with the x-y plane. Grid **112** includes "j" number of cell arrays **132** per row, and "k" number of rows of cell arrays **132** along the z-axis, such that grid **112** includes a total number of j×k cell arrays **132**, and a total number of i×j×k cells **114** (same number as above for cell arrays **120** along the z-axis).

Computer **12** may proceed to a first cell array **132** (step **80** of method **76**), which may located at any suitable location within grid **112**. For convenience, the first cell array **132** may be a corner cell array, such as cell array **132***a*, which is located in the first row at the corner of top side **118***a*, front side **118***b*, and right side **118***c*. Pursuant to steps **82-94** of method **76**, computer **12** then analyzes cells **114** in cell array **132***a* in a leftward direction, as illustrated by arrow **134**.

After cell array **132***a* is analyzed, computer **12** then proceeds to the next cell array **132** (step **96**). In the current example, the next cell array **132** is the adjacent cell array **132** in the first row along the y-axis, referred to as cell array **132***b*. Pursuant to steps **82-94** of method **76**, computer **12** then analyzes cells **114** in cell array **132***b* in a leftward direction, as illustrated by arrow **136**. Computer **12** may then repeat steps **82-96** of method **76** for each successive cell array **132** in the current row along the y-axis. When the first row of cell arrays **132** have been analyzed, computer **12** may then proceed to the first cell array **132** in the second row of cell arrays **132**, and may repeat steps **82-96** for each cell array **132** in the second row, and for each remaining row of cell arrays **132** until all cell arrays **132** of grid **112** are analyzed.

This is shown in FIG. **11**, where cell arrays **132** extend along the y-axis, between right side **118***c* and left side **118***f*. Cell arrays **132** may be analyzed in the same manner as discussed above for cell arrays **120**, where the first cell **114** in each cell array **132** is located adjacent to right side **118***c*, and the last cell **114** in each cell array **132** is located adjacent to left side **118***f*. Therefore, for each cell array **132**, cells **114** are pinged from right-to-left during steps **84-92** of method **76** (e.g., as illustrated by arrows **134** and **136**).

When a given pinged cell **114** includes a subset of the tree data structure for digital part **46** (steps **84** and **86**), computer **12** then designates the pinged cell and all remaining subsequent and unchecked cells **114** in the current cell array **132**, leftward toward the last cell **114**, as being "filled" (step **92**). Accordingly, after computer **12** completes the analysis of steps **80-104**, the cells **114** designated as filled extend leftward, as shown in FIG. **11**. Thus, the resulting calculated support material volume is based on this leftward arrangement, which corresponds to a situation in which digital part **46** is oriented such that the positive direction along the y-axis becomes the upward direction for printing 3D part **32**.

Computer **12** then checks whether the positive direction of the y-axis is the last directional axis to analyze (step **104**). Under the current situation, computer **12** may proceed to the next directional axis (step **106**) and repeat steps **80-106**.

As shown in FIG. **12**, the next directional axis may be the negative direction along the y-axis. In this case, the same cell arrays **132** are used, but are analyzed in an inverted manner compared to the previous operation shown in FIGS. **10** and **11**. In other words, the first cell **114** in each cell array **132** is located adjacent to left side **118***f*, and the last cell **114** in each cell array **132** is located adjacent to right side **118***c*. Therefore, for each cell array **132**, cells **114** are pinged rightward during steps **84-92** of method **76**, as illustrated by arrow **138**.

When a given pinged cell **114** includes a subset of the tree data structure for digital part **46** (steps **84** and **86**), computer **12** then designates the pinged cell and all remaining subsequent and unchecked cells **114** in the current cell array **132**, rightward toward the last cell **114**, as being "filled" (step **92**). Accordingly, after computer **12** completes the analysis of steps **80-104**, the cells **114** designated as filled extend rightward, as shown in FIG. **12**. Thus, the resulting calculated support material volume is based on this leftward arrangement, which corresponds to a situation in which digital part **46** is oriented such that the negative direction along the y-axis becomes the upward direction for printing 3D part **32**.

Computer **12** then checks whether the negative direction of the y-axis is the last directional axis to analyze (step **104**). Under the current situation, computer **12** may proceed to the next directional axis (step **106**) and repeat steps **80-106**. For example, the next directional axis may be the positive direction along the x-axis.

As shown in FIG. **13**, for the positive direction along the x-axis, cells **114** are arranged in multiple cell arrays, referred to as cell arrays **140** extending laterally along the x-axis between front side **118***b* and rear side **118***e* (not shown in FIG. **13**). Each cell array **140** includes "i" number of cells **114** along the x-axis. For ease of discussion, cell arrays **140** may be organized into rows aligned with the y-z plane. Grid **112** includes "j" number of cell arrays **140** per row, and "k" number of rows of cell arrays **140** along the z-axis, such that grid **112** includes a total number of j×k cell arrays **140**, and a total number of i×j×k cells **114** (same number as above for cell arrays **120** along the z-axis, and of cell arrays **132** along the y-axis).

Computer **12** may proceed to a first cell array **140** (step **80** of method **76**), which may located at any suitable location within grid **112**. For convenience, the first cell array **140** may be a corner cell array, such as cell array **140***a*, which is located in the first row at the corner of top side **118***a*, front side **118***b*, and right side **118***c*. Pursuant to steps **82-94** of method **76**, computer **12** then analyzes cells **114** in cell array **140***a* in a rearward direction, as illustrated by arrow **142**.

After cell array **140***a* is analyzed, computer **12** then proceeds to the next cell array **140** (step **96**). In the current example, the next cell array **140** is the adjacent cell array **140** in the first row along the x-axis, referred to as cell array **140***b*. Pursuant to steps **82-94** of method **76**, computer **12** then analyzes cells **114** in cell array **140***b* in a rearward direction, as illustrated by arrow **144**. Computer **12** may then repeat steps **82-96** of method **76** for each successive cell array **140** in the current row. When the first row of cell arrays **140** have been analyzed, computer **12** may then proceed to the first cell array **140** in the second row of cell arrays **140**, and may repeat steps **82-96** for each cell array **140** in the second row, and for each remaining row of cell arrays **140** until all cell arrays **140** of grid **112** are analyzed.

This is illustrated in FIG. **14**, where cell arrays **140** are oriented along the x-axis, between front side **118***b* and rear side **118***e*. Cell arrays **140** may be analyzed in the same manner as discussed above for cell arrays **120**, where the first cell **114** in each cell array **140** is located adjacent to front side **118***b*, and the last cell **114** in each cell array **140** is located adjacent to rear side **118***f*. Therefore, for each cell array **140**, cells **114** are pinged from front-to-rear during steps **84-92** of method **76** (e.g., as illustrated by arrows **142** and **144**).

When a given pinged cell **114** includes a subset of the tree data structure for digital part **46** (steps **84** and **86**), computer **12** then designates the pinged cell and all remaining subsequent and unchecked cells **114** in the current cell array **140**, rearward toward the last cell **114**, as being "filled" (step **92**). Accordingly, after computer **12** completes the analysis of steps **80-104**, the cells **114** designated as filled extend rearward, as shown in FIG. **14**. Thus, the resulting calculated support material volume is based on this rearward arrangement, which corresponds to a situation in which digital part **46** is oriented such that the positive direction along the x-axis becomes the upward direction for printing 3D part **32**.

Computer **12** then checks whether the positive direction of the x-axis is the last directional axis to analyze (step **104**). Under the current situation, computer **12** may proceed to the next directional axis (step **106**) and repeat steps **80-106**.

As shown in FIG. **15**, the next directional axis may be the negative direction along the x-axis. In this case, the same cell arrays **140** are used, but are analyzed in an inverted manner compared to the previous operation shown in FIGS. **13** and **14**. In other words, the first cell **114** in each cell array **140** is located adjacent to rear side **118***e*, and the last cell **114** in each cell array **140** is located adjacent to front side **118***b*. Therefore, for each cell array **140**, cells **114** are pinged forward during steps **84-92** of method **76**, as illustrated by arrow **146**.

When a given pinged cell **114** includes a subset of the tree data structure for digital part **46** (steps **84** and **86**), computer **12** then designates the pinged cell and all remaining subsequent and unchecked cells **114** in the current cell array **140**, forward toward the last cell **114**, as being "filled" (step **92**). Accordingly, after computer **12** completes the analysis of steps **80-104**, the cells **114** designated as filled extend forward, as shown in FIG. **15**. Thus, the resulting calculated support material volume is based on this forward arrangement, which corresponds to a situation in which digital part **46** is oriented such that the negative direction along the x-axis becomes the upward direction for printing 3D part **32**.

As illustrated in FIGS. **7**A-**7**D and **8-15**, when proceeding to each successive directional axis, computer **12** desirably does not reorient digital part **46**, which can take up valuable processing power. Instead, computer **12** merely designates the given selected directional axis as the new "upward" direction and repeats steps **80-106** for each new upward direction.

Computer **12** may then check whether the negative direction of the x-axis is the last directional axis to analyze (step **104**). In the current example, SIG engine **50** is configured to calculate the support material volume for digital part **46** only along the six major directional axes. As such, computer **12** then selects the directional axis that corresponds to the lowest calculated support material volume (step **68** of method **54**). In this case, computer **12** selects the positive direction along the z-axis, as shown in FIG. **8**, which is the directional axis that corresponds to the lowest calculated support material.

Since this is the same orientation of digital part **46** as received, step **70** of method **54** may be optionally bypassed, and computer **12** may output the support material volume to price quoting program **48** (step **72** of method **54**). Computer **12** may also export new digital part **46***a* (step **74** of method **54**) for printing 3D part **32** with system **10**. However, since digital part **46** and digital part **46***a* have the same orientation, computer **12** may alternatively bypass step **74** of method **54**, and use digital part **46** to print 3D part **32** with system **10**.

As shown, SIG engine **50** is suitable for quickly calculating support material volumes needed to print 3D parts using the steps of methods **54** and **76**. For example, when configured to operate with cells **114** having dimensions of 0.01 inches×0.01 inches×0.01 inches (1×10^{-6} cubic inches per cell), SIG engine **50** can calculate a needed volume of support material for a given 3D part in about 5-10 seconds per directional axis, or 30-60 seconds for all six major directional axes. SIG engine **50** is accordingly suitable in combination with price quoting program **48** to provide instant price quotes. However, SIG engine **50** may also be used in conjunction with a variety of different processes, such as tool-path generation processes, run-time and scheduling determinations, and the like.

For example, as shown in FIG. **16**, when used in conjunction with a tool-path generation process, cells **114** of grid **112** may have dimensions that correspond to a sliced layer increment for printing or otherwise building a 3D part with a particular additive manufacturing system (e.g., system **10**). In this embodiment, the digital part **46***a* exported during step **74** of method **54** may include the oriented part for 3D part **32** (referred to as digital part **148**), and also the digital support layers for support structure **34** (referred to as digital support layers **150**). Furthermore, because cells **114** have dimensions that correspond to a sliced layer increment, SIG engine **50** effectively functions as a high-speed slicing program for orienting and slicing digital part **46** into multiple horizontal layers, and for generating digital support layers **150**.

In one embodiment, SIG engine **50** may also be configured to generate tool-path instructions and other related information for each layer of digital part **148** and digital support layers **150**, and the resulting data may be transmitted to host computer **16** and/or system **10**. System **10** may then print 3D part **32** and support structure **34** based on the received data, where the volume of support structure **34** corresponds to the volume of support material calculated by SIG engine **50**.

For run-time and scheduling determinations, SIG engine **50** may also communicate with one or more scheduling programs. For instance, as shown in FIGS. **17**A and **17**B, which correspond respectively to the illustrations shown in FIGS. **2**A and **2**B, additive manufacturing service units (e.g., the on-demand service unit "REDEYE" of Stratasys, Inc.,

Eden Prairie, Minn.) may schedule time slots for printing jobs on farms of additive manufacturing systems, such as farm **152**. These scheduled time slots are typically organized with scheduling programs, such as scheduling program **152** retained on host computer **16** (or alternatively on server **14** or other suitable computer-based system). Since the run times required to print or otherwise build 3D parts and support structures are also typically dependent on the volume of needed support material, SIG engine **50** may also export a run-time estimate based (at least in part) on the calculated support material volume to scheduling program **152**.

The particular run times are also dependent on other factors, such as the type of additive manufacturing process used, the dimensions and complexities of the 3D parts, the part and support materials used, and the like. For example, a jetting-based additive manufacturing system may include a jetting head with an array of jetting orifices for printing part and support materials. The jetting head typically passes an entire printing surface area during each pass for deposition and curing, regardless of the amount of materials being deposited. As such, the run times for a jetting-based additive manufacturing system can be more dependent on the number of printed layers, rather than the amounts of material deposited per layer.

In comparison, the run times in an extrusion-based additive manufacturing system are based on tool paths. As such, the amounts of material deposited per layer can greatly affect the run times. Accordingly, the run times for a jetting-based additive manufacturing system are typically more consistent compared to those for an extrusion-based additive manufacturing system. Therefore, SIG engine **50** desirably accounts for these discrepancies between the different additive manufacturing processes when outputting run-times estimates to scheduling program **152**.

In one embodiment, SIG engine **50** may function as a learning system, in which the run times for various additive manufacturing processes are recorded and compared to the calculated support material volumes to identify correlations. Based on these learned correlations, SIG engine **50** can then provide more accurate run-time estimates to scheduling program **152** for particular additive manufacturing processes.

The outputted run-time estimates from SIG engine **50** allow scheduling program **152** to then identify available time slots for printing a given 3D part, which may also affect the price quote. Thus, SIG engine **50** and scheduling program **152** may also communicate, together or independently, with price quoting system **48** to generate accurate price quotes, and optionally, run-time estimates.

Although the present disclosure has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the disclosure.

The invention claimed is:

1. A method for using a digital part in an additive manufacturing process, the method comprising:

receiving the digital part on one or more data storage devices of a computer;

generating a data structure for the digital part with the computer, wherein the generated data structure comprises a plurality of subsets based on a geometry of the digital part;

generating a grid of cells for the data structure with the computer, wherein each subset is located in one of the cells, and wherein the cells define a plurality of cell arrays each having a first cell and a last cell offset along a directional axis; and

analyzing the cells in a first cell array of the plurality of cell arrays until one of the cells with one of the subsets is identified, wherein if such a cell is identified, then designating the cells in the first cell array between the identified cell and the last cell in the first cell array as filled such that at least one unanalyzed cell is designated as filled; and

repeating the analyzing step for at least a portion of the remaining cell arrays to determine a total filled volume.

2. The method of claim **1**, wherein the data structure comprises a binary space partitioning tree.

3. The method of claim **1**, and further comprising subtracting a volume of the digital part from the total filled volume to determine a support material volume for a support structure.

4. The method of claim **3**, and further comprising modifying the determined support material volume with the computer based at least in part on a printing style for printing the support structure.

5. The method of claim **3**, and further comprising generating a run-time estimate for printing a three-dimensional part and the support structure using the additive manufacturing process based at least in part on the total filled volume, the determined support material volume, or both.

6. The method of claim **5**, and further comprising communicating the run-time estimate to a scheduling program configured to schedule time slots for a plurality of additive manufacturing systems.

7. The method of claim **3**, and further comprising generating a price quote based at least in part on the total filled volume, the determined support material volume, or both.

8. The method of claim **1**, and further comprising orienting the digital part such that a printing direction extends along the directional axis.

9. The method of claim **1**, and further comprising:

generating tool path instructions for printing a three-dimensional part based on the digital part and for printing a support structure in coordination with the printing of the three-dimensional part; and

printing the three-dimensional part and the support structure based on the generated tool path instructions using an additive manufacturing system.

10. A method for using a digital part in an additive manufacturing process, the method comprising:

(a) providing a grid of cells for a data structure of a digital part stored on one or more data storage devices of a computer, wherein the cells are arranged in cell arrays that extend along a plurality of directional axes;

(b) for at least a portion of the cell arrays extending along a first directional axis of the plurality of directional axes, analyzing the cells of the cell array with the computer until a cell in the cell array containing a subset of the data structure is reached;

(c) designating the reached cell and all remaining cells in the cell array between the reached cell and a last cell of the cell array as filled, wherein at least one of the cells designated as filled is unanalyzed; and

(e) repeating the steps (b) and (c) for at least a portion of the cell arrays along each of the remaining directional axes to determine a total filled volume for each of the directional axes.

11. The method of claim **10**, wherein the data structure comprises a binary space partitioning tree.

12. The method of claim 10, and further comprising subtracting a volume of the digital part from the total filled volume for each of the plurality of directional axes to determine a support material volume for each of the plurality of directional axes.

13. The method of claim 12, and further comprising identifying the directional axis having the lowest determined support material volume.

14. The method of claim 12, and further comprising modifying the determined support material volume with the computer based at least in part on a printing style for printing a support structure.

15. The method of claim 10, and further comprising:

generating tool path instructions for printing a three-dimensional part based on the digital part and for printing a support structure in coordination with the printing of the three-dimensional part; and

printing the three-dimensional part and the support structure based on the generated tool path instructions using an additive manufacturing system.

16. A method for printing a three-dimensional part with an additive manufacturing system, the method comprising:

receiving a digital part on one or more data storage devices of a computer;

generating a data structure for the digital part with the computer, wherein the generated data structure comprises a plurality of subsets based at least in part on a surface geometry of the digital part;

generating a grid of cells for the data structure with the computer-based system, wherein the cells define a plurality of cell arrays;

analyzing the cells in a first cell array of the plurality of cell arrays until one of the cells with a subset is reached, wherein when such a cell is reached, then designating the reached cell and the remaining unanalyzed cells in the cell array as filled;

repeating the analyzing step for at least a portion of the remaining cell arrays to determine a total filled volume;

subtracting a volume of the digital part from the total filled volume to determine a geometry of a support structure;

generating sliced layers for the digital part and the support structure based on the grid of cells; and

generating tool path instructions for each sliced layer.

17. The method of claim 16, wherein the data structure comprises a binary space partitioning tree.

18. The method of claim 17, wherein analyzing the cells comprise pinging the cells.

19. The method of claim 16, and further comprising:

determining a volume of support material for the support structure; and

generating a run-time estimate for printing the three-dimensional part and the support structure based at least in part on the total filled volume, the determined support material volume, or both.

20. The method of claim 16, and further comprising printing the three-dimensional part and the support structure based on the generated tool path instructions using the additive manufacturing system.

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